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OCCUPATIONAL EXPOSURE TO XENON-133 AMONG HOSPITAL WORKERS

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Research report

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ABSTRACT

During procedures for pulmonary ventilation studies on patients in hospitals, xenon-133 may escape into ambient air. Measurements of air concentrations were required to permit an evaluation of the exposure to which hospital workers are subjected.

Two complementary methods of in situ measurements of air concentrations were employed: a commercial air monitor and evacuated blood sampling tubes. Personal dosimeters (TLDs) were exposed simultaneously with the commercial air monitor, and the results were compared.

This report presents the results of the measurements of air concentrations during studies on patients. Substantial leakage of xenon-133 was noted, but workers received less than the maximum permissible dose. Personal dosimeters do not permit accurate evaluation of the skin doses resulting from exposure to xenon-133; measurements of air concentrations are required for such evaluation. A number of procedures are recommended to minimize leakage and personnel exposure.

RÉSUMÉ

Durant les procédures d'examen de la ventilation pulmonaire des patients dans les hôpitaux, du xénon-133 peut être libéré dans l'air ambiant. Des mesures des concentrations dans l'air étaient requises pour permettre une évaluation de l'irradiation des travailleurs de ces hôpitaux.

Deux méthodes complémentaires de la mesure in situ des concentrations dans l'air ont été utilisées: un moniteur d'air commercial et des tubes sous vide pour le prélèvement du sang. Des dosimètres personnels (TLD) ont été exposés simultanément en présence du moniteur d'air; les résultats sont comparés.

Le présent rapport présente les résultats des mesures des concentrations lors des examens. Des fuites importantes de xénon-133 se produisent mais n'entraînent pas chez les travailleurs des doses supérieures aux doses maximales admissibles. L'évaluation de la dose à la peau, par exposition au xénon-133, ne peut se faire par les dosimètres personnels; elle requiert des mesures de concentration dans l'air. Des méthodes sont recommandées pour minimiser les fuites et l'irradiation du personnel.

NOTA: Cette publication est aussi disponible en français.

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1. Introduction

Xe-133 has been used for approximately twenty (20) years in nuclear medicine for the study of pulmonary function in certain patients.

Of the 33 isotopes of xenon, atomic numbers 118 to 144, only xenons 127 and 133 are used here in nuclear medicine. The present study deals exclusively with xenon-133, which decays to Cs-133 by β^-, with a half-life of 5.27 days.

The xenon used is in gaseous form; like argon and krypton, xenon is one of the inert gases.

During studies of pulmonary ventilation in patients, some Xe-133 may escape into ambient air. Measurements of air concentrations are required to enable us to evaluate the exposure of personnel in the examining rooms and other members of the department's staff if the xenon does in fact diffuse into their working areas. Two departments of nuclear medicine were selected. Their ventilation systems and dispensing equipment proved to be very different, and the results of the measurements of concentration reflect this fact.

2.1. Description of the procedure for pulmonary ventilation studies

In the two departments of nuclear medicine in which we performed measurements, the procedure for pulmonary ventilation studies was the same. A capsule of gaseous xenon was discharged into the patient's mouthpiece following a deep exhalation; the patient then inhales deeply and maintains a breathhold for approximately ½ minute. The total activity of the xenon is contained in the lungs during this first phase. A clip is placed on the patient's nose prior to introduction of the xenon.

The patient then breathes a mixture of air and approximately 370 MBq (10 mCi) of xenon-133 within a closed circuit for approximately 5 minutes; this is the equilibration phase. The total activity of the xenon is divided between the patient's lungs and the volume of the dispenser's recirculation circuit ± 12 litres (1 or 2 bags of several litres and the connecting tubing). During this time, scintigrams of the patient's pulmonary region are taken by means of a gamma camera.

The following phase, known as washout, in which the patient breathes in an open circuit, lasts several minutes; more scintigrams are taken. The patient inhales ambient air and exhales into an activated carbon trap (Hospital A) or an atmospheric balloon (Hospital B). On completion of this washout stage, the patient is disconnected from the dispensing system, and the nose clip and mouthpiece are removed.

Other scintigrams may be taken to measure continued retention of xenon in the lungs.

The length of the equilibration and washout phases may vary, depending on the condition and co-operativeness of the patient.

2.2. The patient

A look at some of the characteristics of the model [1,2] used for patient dosimetry will help us to understand the results of our measurements more fully. The xenon in the body following a pulmonary ventilation study is described by means of a decay model with five exponential components, their biological half-lives varying from 22 seconds to 10 hours, for subjects with no pulmonary problems.

The most rapid component ($T_{\frac{1}{2}}$ = 22 seconds) involves the air spaces in the lungs, which begin to empty as soon as the washout period begins, while the longest component appears to be related to body fat.

The biological half-lives of the other components are 3 minutes, 24 minutes and 2.7 hours.

3. Instrumentation

A device known as the XenoGard* was used to measure the concentration of xenon-133 in the air. The XenoGard measures and integrates air concentrations of xenon. An analog readout indicates the concentration, while two digital readouts show the time during which integration has taken place and the result in MPC-hours (1 MPC (Maximum Permissible Concentration) for workers exposed to radiation $\approx 10^{-5}$ microCi ml^{-1}).

The XenoGard detector consists of a Geiger tube with a narrow window; a fan circulates the ambient air in a chamber facing the Geiger counter. Both the detector and the chamber are enclosed by 3/8-inch lead shielding.

The measurement levels are 1, 10, 100 and 1000 MPC, values at the top of the scale, with respective response times of 40, 4, 0.4 and 0.04 seconds. Concentrations were measured at 1.2 m from the floor.

We had hoped to take three (3) series of measurements in the examining room. However, the studies were completed within a total of 5 to 10 minutes each; as a result, we did not have time to move the monitor around the room (it is a relatively large piece of equipment), wait for equilibration and note the results. However, it was possible to

* XenoGard, Xenon Room Air and Trap Monitor, Victoreen Model 36-751, Nuclear Associates

use it for continuous measurements of the level at a central point in the room throughout the xenon-133 study and in the other rooms of the department thereafter.

Because of this very fast-moving system (brief study phases) and the monitor's response time, we decided to use a second method of measurement involving the collection of air samples in tubes which we could then evaluate following completion of the study.

Evacuated blood collection tubes were selected because of their ready availability and low cost. Both 7 cc and 15 cc tubes were used; the advantage of the 7 cc tubes is that they can be counted in the automatic counters of the departments of nuclear medicine (if time permits). With these tubes, we can take air samples as close as we wish to the patient's mouthpiece, the outlet from the xenon traps or any other part of the examining room, and do so rapidly, since we need simply pierce the rubber with a needle to allow air to enter; in less than a second, the internal pressure equals the external pressure, we remove the needle, and the rubber seals the tiny needle hole.

The blood collection tubes used are manufactured by the Sherwood Company: Monoject, Evacuated Blood Collection Tubes, Red Stopper, no additives.

3.1. Calibration

In order to test the calibration of the XenoGard and to calibrate the tubes, we released xenon-133 in a closed room. Since the relative error (at 130 MPC) of the XenoGard's response in relation to the activity provided by the company supplying the Xe-133 was less than 7%, we accept the XenoGard's response as accurate.

In the process of changing the air in the room and resealing it, we obtained a number of concentrations at which we took air samples with the tubes and readings with the XenoGard. The concentrations varied from 130 MPC to 0.1 MOC.

The calibration curves for the 7 and 15 cc tubes are shown in figures 1 and 2. The counter is from Radioprotection Inc; it consists of a LUDLUM single channel, model 2200, and a model 243 well crystal; the detector is 2 inches by 1 3/4 in NaI(Tl), and the dimensions of the well are 5/8 by 1 1/2 inch.

Regression lines were plotted by means of the method of least squares, causing intercept at 0. The coefficients of correlation are 0.999156 for the 7 cc tubes and 0.998233 for the 15 cc tubes. Four (4) tubes of each size were filled at each of the concentrations; the results of the individual counts are shown in figures 1 and 2. We can conclude that the vacuum in the tubes is constant for our type of measurements.

The minimum concentration which we can measure by means of the tube method is 1 MPC for reasonable count times.

We also wanted to determine whether there was any substantial leakage of xenon through the rubber stoppers of the collection tubes[3]. A tube showing a high concentration was counted for a period of 2 $T_{\frac{1}{2}}$. Figure 3 shows the theoretic decay curve and the experimental points. The theoretic decay constant is $5.48 \times 10^{-3} h^{-1}$; the experimental points give us a λ value of $5.708 \times 10^{-3} \pm 3.3 \times 10^{-5} h^{-1}$. The difference after 2 X $T_{\frac{1}{2}}$ is less than 6% in relation to the theoretic curve; we can therefore use these tubes since leakage through the rubber stoppers is minimal.

4. Characteristics of the two departments of nuclear medicine visited

4.1 Department of nuclear medicine, Hospital A

The department of nuclear medicine in Hospital A occupies an entire floor of one wing of this hospital, an area of approximately 490 m^2. A floor plan of the department is shown in figure 4, with a description of the uses of the various rooms. Approximately ten (10) pulmonary ventilation studies involving xenon-133 are performed each week, primarily in the room containing stations 4 and 5 and preferably in late afternoon. This room is shown in figure 5.

4.1.1. Ventilation in department A

The fume hoods in the hot laboratory, with a total flow of 1670 cu ft/minute*, and a 2 inch pipe at station 5, which can handle a flow of 4 cu ft/minute but is not used, are the only air outlets from the department. A closed-circuit air-conditioning system is installed in the half of the department where stations 6 and 7 are located.

There is no major ventilating system in this department. The windows must be closed for proper operation of the electronic equipment and computers.

* Anemometer Model 3000, Airflow Developments Ltd, Mississauga

4.1.2. Handling of Xe-133

The xenon-133 is received in glass ampuls with rubber stoppers (FROSST); each ampul contains a single dose and is calibrated at 10 milliCi for 1 pm Wednesday. Thus, unless the doses are kept for the following week, the activities for patients may vary from 7.5 milliCi to 13.3 milliCi.

Department A has a PULMONEX* device tc dispense the Xe-133 to the patient. This system is enclosed in 1/16-inch lead shielding (including two lead windows for viewing the pneumatic bags). The system includes an activated carbon filter, which traps the xenon from the patient as well as that contained in the tubing and bags required by the system. The activated carbon trap is enclosed in 1/8-inch lead shielding.

A diagram of the PULMONEX is shown in figure 6. The manufacturer recommends that the activated carbon trap be changed annually.

* Pulmonex Xenon System
Atomic Products Corporation

4.2. Department of nuclear medicine, Hospital B

The department of nuclear medicine in Hospital B also occupies the entire floor of one wing of the hospital, an area of approximately 1100 m^2. The uses of the various rooms are listed in figure 7. The workload includes approximately ten (10) xenon-133 studies a week. The studies are carried out at any time and we performed measurements in three (3) different rooms. These rooms are shown in figures 8, 9 and 10.

4.2.1. Ventilation in department B

An independent, non-recirculating ventilation system serves the entire nuclear medicine wing. It provides 5.5 air changes an hour; however, the flow may vary considerably from room to room, as we can see in figures 7, 8 and 9.

The 2 fume hoods in the hot laboratory (m2-42) have a total flow of 620 cu ft/min.

4.2.2. Handling of Xe-133, Hospital B

The xenon-133 is obtained from the Frosst Company as well, and the characteristics are the same as in department A, as described in 4.1.2.

Department B has a "home-made" system for dispensing xenon-133. The upper portion of the system is enclosed, on the patient's side only, by 1/16-inch lead shielding, while the meteorological bag used to recover the xenon has 0.5 mm of shielding. This system uses only one pneumatic bag.

The diagram representing this xenon dispenser is shown in figure 11. On completion of the study, the meteorological bag is placed under a fume hood to empty. The pneumatic bag is not emptied during the washout phase of the study.

5. Measurements of air concentrations

During pulmonary ventilation studies, air concentrations of xenon-133 were measured in the examining room by means of evacuated blood collection tubes. The XenoGard took continuous measurements approximately 1.5 metres from the patient; these measurements were registered on a strip recorder operating at a paper speed of one (1) inch/5 minutes. The same XenoGard was used for measurements throughout the department as a whole.

The objective for each study was 27 sample tubes in the examining room, including one measurement of the level in room air prior to the study. For several patients, we were unable to collect the 27 samples since certain stages of the study had to be cut short by the technician, or the patient simply removed the mouthpiece because of breathing difficulties.

5.1 Results for patients in Hospital A

5.1.1. Examining room

Table 1 shows the different sites at which air samples were taken for patients in Hospital A, and the concentrations measured.

The studies on patients 1, 2, 4 and 5 were performed at station 4, while patient 3 was examined at station 5. The sampling sites are indicated in figures 12 and 13. Stations 4 and 5 are two independent

systems with gamma cameras and data processing in the same room of the department.

The xenon-133 activities used were as follows: 7.7, 7.7, 13 and 10 millicuries for patients 1 to 5 respectively.

Table 1 indicates that the concentrations measured, during the equilibration and washout phases and on the first expiration (measurement 20) following removal of the mouthpiece, frequently vary by more than an order of magnitude. The variations thus do not relate exclusively to the activities of xenon-133 used (maximum variation of a factor of 2) but to the patient himself and his problems maintaining good mouth-mouthpiece contact and keeping the mouthpiece in until completion of the study.

Mathematical averaging of the measurements taken two (2) minutes following completion of the study on the patient (measurements 21 to 27) gives us mean concentrations and variances (σ_{n-1}) of 7.5 ± 1.7, 2.4 ± 1.0, 9.1 ± 2.3, 8.5 ± 2.5 and 1.3 ± 0.4 MPC. During the study, the door was generally shut only in the first two cases (except for staff entering and leaving).

If this value did in fact correspond to the mean concentration in the room, we would find losses of 100, 31, 70, 65 and 13% respectively of the xenon-133 originally contained in the ampul.

The xenon trap, which consists of an activated carbon filter, can be considered at least partially responsible for excessive losses (measurements 15). The PULMONEX system has been in operation for five (5) years and the activated carbon filter has never been changed. The manufacturer recommends that it be changed every year. However, cases 2 and 5 indicate that the trap is operating with some degree of efficiency, since leakage from all causes appears to be limited here to 3% and 1%.

The major problem, then, appears to be related to the difficulty experienced by the patient in maintaining good mouth contact with the mouthpiece. The mouthpiece used here has no strap to hold it in the mouth. However, it is not used in accordance with the manufacturer's instructions, which recommend that the flange be placed between the teeth and the lips to ensure a good seal. Here, the flange of the mouthpiece is placed inside the teeth, a method which does not ensure an acceptable seal, as our measurements show.

The air sample (N° 20) taken from the first exhalation following disconnection from the system shows clearly that, even after several minutes of washout, some patients retain a substantial level of xenon activity. This study appears to be difficult for the patients, all of whom have respiratory problems, and in some we note that the first "free" exhalation is exceptionally deep, as if to say, "Whew! At last I can breathe". While they were connected to the system, they may have been

breathing superficially. With this first exhalation, they appear to empty the deepest air spaces in their lungs.

For some of these patients too, the scintigrams may indicate, even at the end of the washout period, that a given region of the lungs is not functioning properly. This region thus retains the xenon for a longer period than the other regions of the lungs and continues to empty after the patient is disconnected from the system.

Figure 14 shows some of the recorded concentrations, using the XenoGard, in maximum permissible concentrations (MPC) units, over time. Here we can see the results of a xenon-133 study in the room followed by 3 pulmonary ventilations using Xe-133. From similar curves, we have calculated that the rate of xenon-133 reduction in the room containing stations 4 and 5 was 0.6 to 1.9% a minute.

5.1.2. Measurements in the department

The XenoGard, with a strip recorder, was used for measurements in the department. Since these measurements were taken following completion of the patient studies, we had the time and room required to move the XenoGard around on a cart. Because the concentrations found were also

lower, the collection tube method was no longer suitable.

In Hospital A, we found xenon diffused throughout the entire department, because of the total lack of forced-air ventilation.

If in fact no air change had taken place, we would have found a concentration, at equilibration, 1/10.7 times the initial concentration in the room containing station 4 and 5 (ratio of the volume of the room to that of the department). In fact, some air change does take place through the fume hoods, the doors of the department and the numerous windows.

Figures 15, 16 and 17 show the results in the department of the measurements of air concentrations for the five (5) cases of pulmonary ventilation previously cited for the same department. Within 2 to 3 hours of the beginning of the study, we found xenon-133 throughout the department in all cases. The farther the rooms were located from the examining room, the lower the concentrations.

Air concentrations were measured, with the XenoGard and the vacuum tubes, 1.2 m from the floor.

5.2 Results for patients in Hospital B

5.2.1. Examining rooms

Table 2 indicates the different points at which air samples were taken for patients in Hospital B, and the results of these measurements.

The studies on patients 1 and 3 were performed in room 40, on patients 2 and 4 in room 16, and on patient 5 in room 46. The sampling sites are shown in figures 18, 19 and 20.

The door of room 16 remained closed during the study, while the doors of the other rooms remained open.

The ampuls of xenon-133 contained activities of 8.8, 11.4, 11.4, 13 and 3 millicuries for patient 1 to 5 respectively.

The fifth patient was a baby several months old, who lay directly on the camera, which was placed horizontally in this instance.

For all patients, with the exception of the fourth, the measurements of xenon concentrations in the air varied only slightly during the different phases of pulmonary ventilation.

If we compare the mean of the concentrations measured during the washout portion of the studies, samples 11 to 19, which is 9.4 $\pm$ 6.5 (σ_{n-1}) MPC, with the mean for Hospital A during the same phase of the study, which is 7.9 $\pm$ 11.7 (σ_{n-1}) MPC, we see that the same amount of leakage occurred in both hospitals. (For Hospital A, sample 15 was not included because it was taken at the outlet from the carbon filter).

We also note substantial variations from one patient to another and a great deal of difficulty maintaining good mouthpiece-mouth contact in the patient.

In figures 18, 19 and 20, we see the air inlets and outlets for each of the rooms. We cannot assume that equilibrium is established in the room during the few minutes the study requires.

From sample N° 20, we see that only patient 4 maintained a breathhold throughout the study; the other patients do not appear to have had any problem overcoming the slight resistance of the xenon-dispensing system.

From the paper strips recording the XenoGard's response, we can calculate that the rate of Xenon reduction in the various rooms of this department ranges from 10 to 16% a minute.

5.2.2. Measurements in department B

As explained in 5.1.2., the XenoGard was used.

The measurements taken following the study on patient 5 indicated that there was no xenon-133 (< 0.05 MPC) outside room M2-46.

The results of the measurements for the other patients, figures 21, 22 and 23, show very low concentrations for maximum periods of only ten or twenty minutes.

However, a recording taken in room 40 showing a second peak approximately 10 minutes after completion of the study indicates that the pneumatic bag did not empty into the meteorological balloon but into the room instead. This system for dispensing xenon-133 during ventilation studies does not permit the pneumatic bag to empty into the meteorological balloon during the washout phase, and the technician must therefore open the valve in order to empty it; however, the meteorological balloon is removed immediately after the study to minimize external irradiation and the possibility of xenon leakage into the room.

6. Exposure of personnel

In addition to the technician who is with the patient in the examining room, several other staff members may be exposed to varying concentrations of xenon-133 in departments of nuclear medicine. Ventilation and geographic location with respect to the examining room are the chief factors influencing personnel exposure.

A recent study [4] indicates that the limiting factor is radiation to the skin for immersion in a small-diameter (radius 2-3 metres) cloud of xenon-133 gas. The same study indicates, for β radiation, exposure of 0.312 mrem/hour/MPC at a depth of 70 microns (8 mg/cm^2) surface dose equivalent, for X and γ rays of 30 KeV and 80 KeV show values of 0.00540 mrem/MPC-hour (30 KeV) and 0.00242 mrem/MPC-hour (80 KeV) at a cloud radius of 2 metres, while the corresponding values at 3 metres are 0.00803 and 0.00363 mrem/MPC-hour respectively.

The dose equivalent rate for X and γ rays at the surface of the skin, plus the dose equivalent rate at 70 microns for β radiation, give a total of 0.320 and 0.324 mrem/MPC-hour respectively at cloud radii of 2 and 3 metres.

Given the dimensions of the examining rooms, we can take an effective cloud radius of 2 to 3 metres for xenon-133. As described in the preceding paragraph, the dose equivalent is practically the same for these two effective radii. In terms of xenon's β radiation, these clouds are equivalent to infinite clouds. The dose equivalents to personnel will thus be based on a skin dose of 0.32 mrem/MPC-hour.

The International Commission on Radiological Protection (ICRP 30) (5) recommends a DAC (derived air concentration limit) of 2×10^7 Bq m^{-3} for rooms of 1000, 500 and 100 m^3 (radii 6, 5 and 3 m, assuming a sphere of the same volume). From this value we can calculate an average skin dose equivalent of 0.46 mrem/MPC-hr for these three room volumes, a figure compatible with the values which we are using. This DAC value of 2×10^7 Bq m^{-3} is for workers exposed to radiation.

Personnel of departments of nuclear medicine other than the technicians in the rooms where pulmonary ventilations are performed are also exposed to effective clouds at radii of 2 to 3 metres for a skin dose equivalent of 0.32 mrem/MPC-hour.

6.1 Dose equivalents for personnel in Hospital A

Examining room : stations 4 and 5.

The great majority of the pulmonary ventilation studies with Xe-133 are performed in this room.

Two technicians are exposed, one at each station.

The XenoCard was used in this room, for integration over a period of two weeks; an average value of 3.3 MPC-hour was obtained for each pulmonary study (average for 13 studies in the room containing stations 4 and 5).

For the other sectors of the department, the integrated values in MPC-hour units are drawn from figures 15, 16 and 17. The department was divided into 4 regions for the purposes of integration.

It should be noted here that 3 pulmonary ventilations with Xe-133 had been performed at the time measurements were taken on patients N° 1 and N° 2; total exposure was therefore divided by 3. Similarly, patients N° 3 and N° 4 were done in succession, and the values shown thus represent a total value divided into two equal parts.

Exposures in MPC-hours and mrem at the skin are shown in table 3. We have also shown the average values for patient exposure in MPC-hours.

Although these divisions of the department are entirely arbitrary, the fact remains that workers in the reception area and other nearby rooms where xenon-133 is not used are exposed, on the whole, to as much xenon as the technicians who perform the pulmonary ventilations. Members of the personnel group between these two extreme groups are themselves exposed to nearly twice as much, in MPC-person-hours, as the two technicians involved.

Assuming that ten (10) Xe-133 studies are performed each week, the exposure of every member of the department is still well below the standards. The technicians at stations 4 and 5 would receive 5 mrem at the skin, compared to the limit of approximately 600 mrem a week (30 rems ÷ 50 weeks), assuming they are atomic radiation workers. If they are not atomic radiation workers, they would receive 5 mrem at the skin out of a permissible maximum of 60 mrem a week, solely as a result of procedures involving xenon-133.

6.2 Dose equivalents for personnel in Hospital B

Figures 21, 22 and 23 show that, outside the examining rooms, personnel exposure is less than 0.1 MPC-hr in all cases; skin exposure is thus well below 0.1 mrem for each study as well.

From the same figures 21, 22 and 23, we obtain the values presented in table 4 for exposure of technicians present in the examining room during studies with xenon-133.

The mean for technicians of 1.2 ± 0.2 MPC-hr for a corresponding skin exposure of 0.4 ± 0.1 mrem is similar to the result obtained at Hospital A, where we found 1.5 ± 0.8 MPC-hr and 0.5 ± 0.3 mrem.

The major difference lies in the fact that at Hospital B, only the technician performing the Xe-133 study is exposed, for a total of 1.2 MPC-person-hours for each study, in contrast to the 11.6 MPC-person-hours at Hospital A.

Patient 5 was not included in table 4 since an unusually large number of people were required in the room. Our measurements cannot be representative of the concentrations for the personnel, who had to be very close to the patient (a baby), and the only remaining position for us was near the air inlets to the room.

In Hospital B, then, xenon-133 leakage is at least as great as at Hospital A, but because of the impressive ventilation system, exposure of departmental personnel is very limited.

7. Measurement of exposure by thermoluminescent dosimeters

In most departments of nuclear medicine, the only method of dosimetry used is the personal dosimeter; this service is offered by the Radiation Protection Bureau of the Department of Health and Welfare.

We therefore wished to determine whether the results from personal dosimeters (TLDs) agree with the results from measurements of air concentrations as measured by the XenoGard.

The principal forms of radiation to be measured are: beta, 346 keV (max), 99%; X-rays, 30 and 35 keV, total 47%; and gamma, 81 keV, 37%.

As described by Piltingsrud and Gels (4), the skin dose is the limiting factor for small-dimension xenon clouds like those which occur in departments of nuclear medicine. The same publication recommends the use of a factor of 0.312 mrem/hr/MPC for the skin dose at 70 microns. If we add the contribution of the 30 and 80 keV X and γ rays, we obtain a total of 0.320 and 0.324 mrem/hr/MPC at cloud radii of 2 and 3 metres respectively. We shall therefore use a factor of 0.32 mrem/MPC/hr.

According to the same publication, body doses are 44 and 30 times less than skin doses at cloud radii of 2 and 3 metres.

Personal dosimeters (TLDs) were exposed in the presence of the XenoGard, and exposure in MPC-hours was integrated by the XenoGard.

One series of dosimeters was not exposed to xenon (my office). Another two series were carried around during measurements with patients in both departments of nuclear medicine; these dosimeters were exposed to 7 MPC-hr and 15 MPC-hr. A third group of 12 dosimeters was left in the department

of nuclear medicine at Hospital A for an exposure of 102 MPC-hours. The dosimeters were thus exposed to forms of radiation other than xenon-133, since patients were assessed in these rooms with other radioisotopes, particularly Tc-99 m; a special room is set aside for iodine.

The results for the personal dosimeters are shown in table 5.

The dosimeters were read by the Radiation Protection Bureau; the results for the TLD-100s are based on the standard calibration for Cs-137. For the skin dose, a TLD-100 measuring 3.2 X 3.2 X 0.38 mm and covered by 7 mg/cm^2 aluminised mylar is used [6].

The mean responses and standard deviations are shown in table 6 for the four (4) groups of dosimeters. The dosimeters exposed to 7 and 15 MPC-hr showed no difference for additional skin doses of 2 and 5 mrem, since these doses were too small. As regards the case involving exposure to 102 MPC-hr (32 mrem at the skin), we are very interested in what the personal dosimeters can tell us.

For the 12 dosimeters exposed to 102 MPC, the "true" skin dose was evaluated by subtracting from the skin dose of each of the thin TLDs the average body dose for the 12 3.2 X 3.2 X 0.89 mm TLD-100s under 2 mm of aluminum (true skin DE = skin DE - body DE). The 12 dosimeters had been exposed to the same conditions.

Table 5 indicates the "true" skin dose for each of the dosimeters exposed to 102 MPC-hr and the percentage of this "true" dose in relation to the 32 mrem exposure. The average value is 68% (σ_{n-1} = 65%) of the exposure. Individual dosimeters produced results varying from 0% to 159% of the "true" exposure.

The average value of 68% is acceptable for such low exposure; however, in practice, a worker wears only one dosimeter and we therefore have to look exclusively at the individual results, which show a range of 0 to 159%. Individually, then, a dosimeter cannot indicate this skin exposure of 32 mrem.

Energy dependence under 2 MeV is very high for TLDs exposed to β radiation; this effect is clearly illustrated in an article by Jones[7] for TLD-100s 0.9 and 0.25 mm thick. Some of these values are shown in table A.7, reference 6. The values for the 0.38 mm thick crystals used should be somewhat different.

In addition, in the dosimeters, the TLDs are covered by 2 mm of 7 mg/cm^2 aluminum, representing substantial absorption for beta radiation from xenon-133, the maximum energy of which is 346 keV.

The dosimeters are calibrated with Cs-137 and it is impossible to correct them for β radiation, since the dosimeter cannot provide information on incident energy.

Of the three (3) companies offering TLD dosimeters tested by Piltingsrud and Gels [4], only one detected exposure, but at an average value of only 3.54%; individual values vary from 0 to 7.1% for exposures of 258 to 1917 mrem at the skin. The Radiation Protection Bureau's dosimetry service is thus far superior in terms of average exposure. However, on an individual basis, responses are erratic for all services.

In practice, the Radiation Protection Bureau would assign a skin dose equal to the body dose for the 12 dosimeters exposed to 102 MPC-hr during the experiment, since if the estimated value of the skin dose

does not exceed the body dose by more than 100 mrem, its indicated value is the same as the body dose. For technicians at Hospital A, this unindicated skin dose would correspond to approximately 100 studies for each three (3) month wearing period (100 mR (skin) ÷ $\frac{32 \text{ mR}}{\text{MPC.hr}}$ ÷ $\frac{3.2 \text{ MPC.hr}}{\text{study}}$) .

The maximum annual theoretic exposure which could be overlooked is thus 400 mrem at the skin (4 wearing periods), an acceptable practice[8] for atomic radiation workers.

The departments visited performed an average of 10 studies a week with xenon-133, for a total of approximately 120 studies during each dosimeter wearing period. Several technicians share responsibility for the studies within a single department, and it is therefore highly unlikely that a single technician would perform 100 studies; it is also highly unlikely that exposure to xenon-133 will be included in the workers' files.

For a quantitative evaluation of the exposure of atomic radiation workers and others in hospital departments of nuclear medicine, measurements of air concentrations are necessary. However, it has been shown in the present study that, with a workload of 10 patients a week under the worst conditions (no ventilation system), skin exposure is low and well below the maximum permissible limit for atomic radiation workers who are not considered atomic radiation workers.

8. Reduction of exposure to xenon-133

Workers in hospitals will not be exposed beyond maximum permissible limits; however, a number of procedures should be observed to maintain doses at levels as low as possible (ALARA) in two cases: normal situations and emergency situations.

8.1 Normal situations

The measurements performed in our study indicate that leakage of xenon-133 can be detected regularly, even during entirely normal studies in which everything proceeds normally.

The greatest leakage occurs at the contact of the mouthpiece and the patient's mouth; it is important, therefore, to ensure that the mouthpiece is used in accordance with the manufacturer's specifications to maximize lip contact with the mouthpiece.

As regards the dispenser, the design should be checked to ensure that, during each phase of the study, and even after its completion, all components empty into a bag or into the activated carbon trap. The xenon-133 dispenser should be enclosed in 1/16-inch lead shielding on all sides. The capsules containing the xenon-133 should be transported as well in 1/16-inch lead containers to minimize external irradiation; measurements have been performed by Loken and Kush [9] with 30 mCi of xenon-133.

The effectiveness of the xenon traps (activated carbon) should be checked at regular intervals of no more than three (3) months; manufacturers recommend that they be replaced annually. These traps are not 100% effective.

In order to minimise the exposure of personnel to xenon in the air, good ventilation to the outside is required. Department B offers a good example of very powerful ventilation without recirculation. In the case of department A, a simple window fan would be enough to remove the xenon rapidly to the outside. At the very least, in order to deal with the xenon problem, this fan could be turned on at the beginning of each study (door open) and turned off at the end.

One source of xenon which should not be overlooked is the patient who has completed his study. The patient continues to exhale xenon-133, and the more severely his lungs are affected, the longer he will do so; as a result, he should be placed in a well ventilated location.

Departments of nuclear medicine should perform annual tests to ensure that exposure is kept at the lowest possible level; the only effective method of doing so is to measure air concentrations with an appropriate instrument [10] or evacuated tubes, as described in chapter 3, for which calibration is required.

Gaseous xenon-133, packed in single doses (FROSST) in glass ampuls with rubber stoppers, is safer than gaseous xenon or xenon in saline in a syringe.

Counting of single-dose ampuls before and after injection indicates that over 98% of the xenon is evacuated on injection. The device used to inject the xenon has two needles which can be plugged with particles of rubber; when activities of $\pm$ 1 Ci are transferred in certain sophisticated dispensers, good ventilation is essential.

It is recommended that xenon be stored in a well ventilated location.

Xenon in a syringe, in the gaseous form or in saline, shows greater leakage, as described by Benedetto and Landry[11]. For example, a high percentage of the dose may remain in the syringe following the injection; hence, good waste handling techniques are essential to minimize personnel exposure. The centres in which the single doses are made up, often from an initial activity of 1 Ci of gaseous xenon-133, should have a xenon air monitor operating constantly during such operations; handling should take place under a good fume hood, and the flow from the hood should be measured at least once a year.

8.2 Emergency situations

In some cases, patients are unable to tolerate the mouthpiece for the entire period of the study; they may remove it and exhale into the room. The percentage of these cases will vary considerably from hospital to hospital; in one of the departments visited, this occurred in approximately 10% of all cases.

If the mouthpiece is removed immediately following the injection of xenon-133, loss into the room is nearly 100%.

In Hospital A, the fan suggested earlier should be turned to a higher speed, or a second window fan turned on, again with the door open. This fan or fans should remain in operation for at least 15 minutes after such an incident.

In Hospital B, the door of the examining room should be kept closed in such cases for at least 15 minutes, to ensure that the xenon does not escape into the rest of the department.

In these emergency situations, only the technician should remain in the room with the patients.

9. Conclusion

Measurements of air concentrations of xenon-133 during pulmonary studies on patients have shown that substantial leakage occurs. However, it is highly unlikely that hospital personnel receive skin doses exceeding the maximum permissible levels, whether or not they are atomic radiation workers, despite a wide range of ventilation conditions.

Exposure could be substantially reduced if patient procedures were regularly reviewed, measurements of air concentrations performed periodically and distribution equipment properly maintained and tested.

The results shown by personal dosimeters are not reliable for the levels of xenon-133 exposure encountered in departments of nuclear medicine. When measurements of air concentrations are required, continuous integrating devices are available and recommended; in addition, a method developed for this study using evacuated blood collection tubes has been found effective for this purpose.

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Table 1.

Air concentrations, patients in Hospital A.

	SAMPLING SITE	PATIENT: 1	2	3	4	
1-	Level prior to injection	-	1,8	-	1,5	-
2-	Injection (30 cm, facing patient)	-	2,1	-	2,6	1.
3-	Equilibration (10 cm, facing patient)	-	1,9	3,6	3,4	1.
4-	" (1 m, facing patient)	-	1,4	-	2,9	-
5-	" (1 m, right of patient)	2,6	2,1	23,4	1,6	-
6-	" (1 m, left of patient)	17,1	1,0	3,2	2,6	1,
7-	" (2 m, facing patient)	-	-	-	3,0	-
8-	" (2 m, to side of patient)	5,1	1,0	1,0	3,3	-
9-	" (1 m, ahead of patient and 2 m to the side)	2,3	1,1	2,9	2,5	-
10-	" (1 m, ahead of patient and 2 m to the side) <u>or</u>					
	" (1 m, facing other work station)	-	2,0	-	2,7	-
11-	Washout (10 cm, facing patient)	48,6	1,5	51,0	4,9	3,
12-	" (1 m, facing patient)	8,9	1,2	9,8	2,5	-
13-	" (1 m, right of patient)	7,1	1,7	22,3	2,4	1,
14-	" (1 m, left of patient)	8,5	4,5	9,6	1,5	5,
15-	" (outlet: Xe-133 dispenser)	X	118,1	360,1	73,2	605,
16-	" (2 m, facing patient)	X	1,8	10,9	4,4	-
17-	" (2 m, to side of patient)	X	1,8	18,4	3,4	-
18-	" (1 m, ahead of patient and 2 m to the side)	X	1,8	22,2	6,9	-
19-	" (1 m, ahead of patient and 2 m to the side) <u>or</u>					
	" (1 m, facing other work station)	X	1,7	9,6	2,1	-
20-	Patient disconnected (30 cm, facing patient)	9,1	226,6	14,8	68,4	22,
21-	" " , + 2 minutes (1 m, facing patient)	6,8	2,9	6,6	8,7	1,
22-	" " , " (1 m, right of patient)	8,1	1,1	12,0	13,1	1,
23-	" " , " (1 m, left of patient)	11,1	2,8	8,2	6,1	-
24-	" " , " (2 m, facing patient)	7,0	3,6	6,1	6,6	1,
25-	" " , " (2 m, to side of patient)	6,2	3,0	8,7	9,6	1,
26-	" " , " (1 m, ahead of patient and 2 m to the side)	6,6	2,3	11,2	9,5	-
27-	" " , " (1 m, ahead of patient and 2 m to the side) <u>or</u>					
	" " , " (1 m, facing other work station)	6,6	1,0	10,9	6,2	-

- indicates < 1 MPC, and X that the measurement was not performed.

Table 2.

Air concentrations, patients in Hospital B.

SAMPLING SITE	PATIENT:	1	2	3	4	5
1- Level prior to injection		-	-	-		-
2- Injection (30 cm, facing patient)		-	-	-	37,2	-
3- Equilibration (10 cm, facing patient)		-	-	-	280	-
4- " (1 m, facing patient)		2,4	-	-	7,1	-
5- " (1 m, right of patient)		1,8	3,6	-	15,5	-
6- " (1 m, left of patient)		7,5	13,4	1,9	7,6	16
7- " (2 m, facing patient)		4,2	14,1	8,0	8,7	1,
8- " (2 m, to side of patient)		4,2	22,7	2,4	-	-
9- " (1 m, ahead of patient and 2 m to the side)		3,9	X	6,3	X	-
10- " (1 m, ahead of patient and 2 m to the side) or		X	X	X	X	-
" (1 m, facing other work station)						
11- Washout (10 cm, facing patient)		7,1	29,5	6,6	22,6	9,
12- " (1 m, facing patient)		3,7	17,8	6,6	11,2	X
13- " (1 m, right of patient)		4,9	13,3	5,4	13,4	X
14- " (1 m, left of patient)		5,0	14,0	5,0	18,1	X
15- " (outlet: Xe-133 dispenser)		3,7	13,8	5,3	13,4	X
16- " (2 m, facing patient)		3,9	11,6	4,7	11,8	X
17- " (2 m, to side of patient)		2,2	X	4,7	X	X
18- " (1 m, ahead of patient and 2 m to the side)		4,0	X	4,4	X	X
19- " (1 m, ahead of patient and 2 m to the side) or		X	X	4,0	X	X
" (1 m, facing other work station)						
20- Patient disconnected (30 cm, facing station)		3,8	5,7	2,2	72,9	7,3
21- " " , + 2 minutes (1 m, facing patient)		2,4	5,5	1,6	13,1	5,3
22- " " , " (1 m, right of patient)		2,1	5,7	1,6	4,7	2,2
23- " " , " (1 m, left of patient)		2,3	4,7	5,3	5,7	2,8
24- " " , " (2 m, facing patient)		1,5	4,2	2,1	6,1	3,0
25- " " , " (2 m, to side of patient)		2,6	4,0	1,8	4,8	2,2
26- " " , " (1 m, ahead of patient and 2 m to the side)		2,1	3,4	1,2	4,4	1,5
27- " " , " (1 m, ahead of patient and 2 m to the side) or (1 m, facing other work station)		1,2	3,5	1,0	4,5	4,0

- indicates 1 MPC, and X that the measurement was not performed.

TABLE 3 Exposure of personnel, Hospital A.

Location	Number of persons exposed	Patient 1	Patient 2	Patient 3	Patient 4	Patient 5	Average/patient
		MPC.hr / mrem (skin)					MPC.hr (σn-1) / mrem (skin) (σn-1)
Stations 4 & 5	2 (A)*	1,2 / 0,4	1,2 / 0,4	2,3 / 0,8	2,3 / 0,8	0,4 / 0,1	1,5 (0,8) / 0,5 (0,3)
Station 6	1 (A)	0,4 / 0,1	0,4 / 0,1	1,1 / 0,4	1,1 / 0,4	0,2 / 0,1	0,6 (0,4) / 0,2 (0,2)
Offices 1.1; 1.2 1.3, 1.5 1.6 and darkroom	6 (A) 2 (B)*	0,4 / 0,1	0,4 / 0,1	1,2 / 0,4	1,2 / 0,4	0,2 / 0,1	0,7 (0,5) / 0,2 (0,2)
Entrance Reception Stations 1, 2 & 7	5 (A) 3 (B)	0,4 / 0,1	0,4 / 0,1	0,4 / 0,1	0,4 / 0,1	0 / 0	0,3 (0,2) / 0,1 (0,04)

* (A) = Technicians and physicians,
(B) = Support staff, members of the public.

Table 4.

Exposure of personnel, Hospital B.

Location	Patient 1	Patient 2	Patient 3	Patient 4	Average/patient
	MPC.hr / mrem (skin)				MPC.hr (σ n-1) / mrem (skin) (σ n-1)
Room 40	1,2 / 0,4				
Room 16		1,3 / 0,4			
Room 40			0,9 / 0,3		
Room 16				1,4 / 0,5	
					1,2 (0,2) / 0,4 (0,1)

Table 5

RESULTS OF PERSONAL DOSIMETERS (TLD-100)

Exposure to xenon		Body dose	Skin dose	"True" skin dose	% skin dose
(MPC-hr)	mSv	(mSv)	(mSv)	(mSv)	
0	0	0,40	0,48		
0	0	0,50	0,61		
0	0	0,54	0,86		
0	0	0,38	0,45		
0	0	0,62	0,52		
0	0	0,46	0,48		
102	0,32	0,70	1,17	0,49	153
102	0,32	0,83	1,12	0,44	138
102	0,32	0,72	1,14	0,46	144
102	0,32	0,71	1,03	0,35	109
102	0,32	0,63	0,81	0,13	41
102	0,32	0,57	0,76	0,08	25
102	0,32	0,60	0,72	0,04	13
102	0,32	0,94	0,75	0,07	22
102	0,32	0,59	0,86	0,18	56
102	0,32	0,58	0,98	0,30	94
102	0,32	0,71	1,19	0,51	159
102	0,32	0,52	0,62	0	0
7	0,02	0,35	0,54		
7	0,02	0,30	0,32		
7	0,02	0,38	0,35		
7	0,02	0,41	0,32		
7	0,02	0,36	0,40		
7	0,02	0,38	0,27		
15	0,05	0,38	0,29		
15	0,05	0,34	0,38		
15	0,05	0,37	0,24		
15	0,05	0,38	0,29		
15	0,05	0,35	0,33		
15	0,05	0,41	0,71		

Table 6

AVERAGE VALUES OF PERSONAL DOSIMETERS

Number of dosimeters	Exposure		Response of TLD-100s	
	MPC.hr	mrem	Average body dose mrem ($\bar{\sigma}$n-1)	Average skin dose mrem ($\bar{\sigma}$n-1)
6	0	0	48 (9)	57 (15)
6	7	2	36 (4)	37 (10)
6	15	5	37 (2)	37 (17)
12	102	32	68 (12)	93 (20)

Figure 1.

COUNTER EFFECTIVENESS FOR 7 cc TUBES (ppm/MPC)

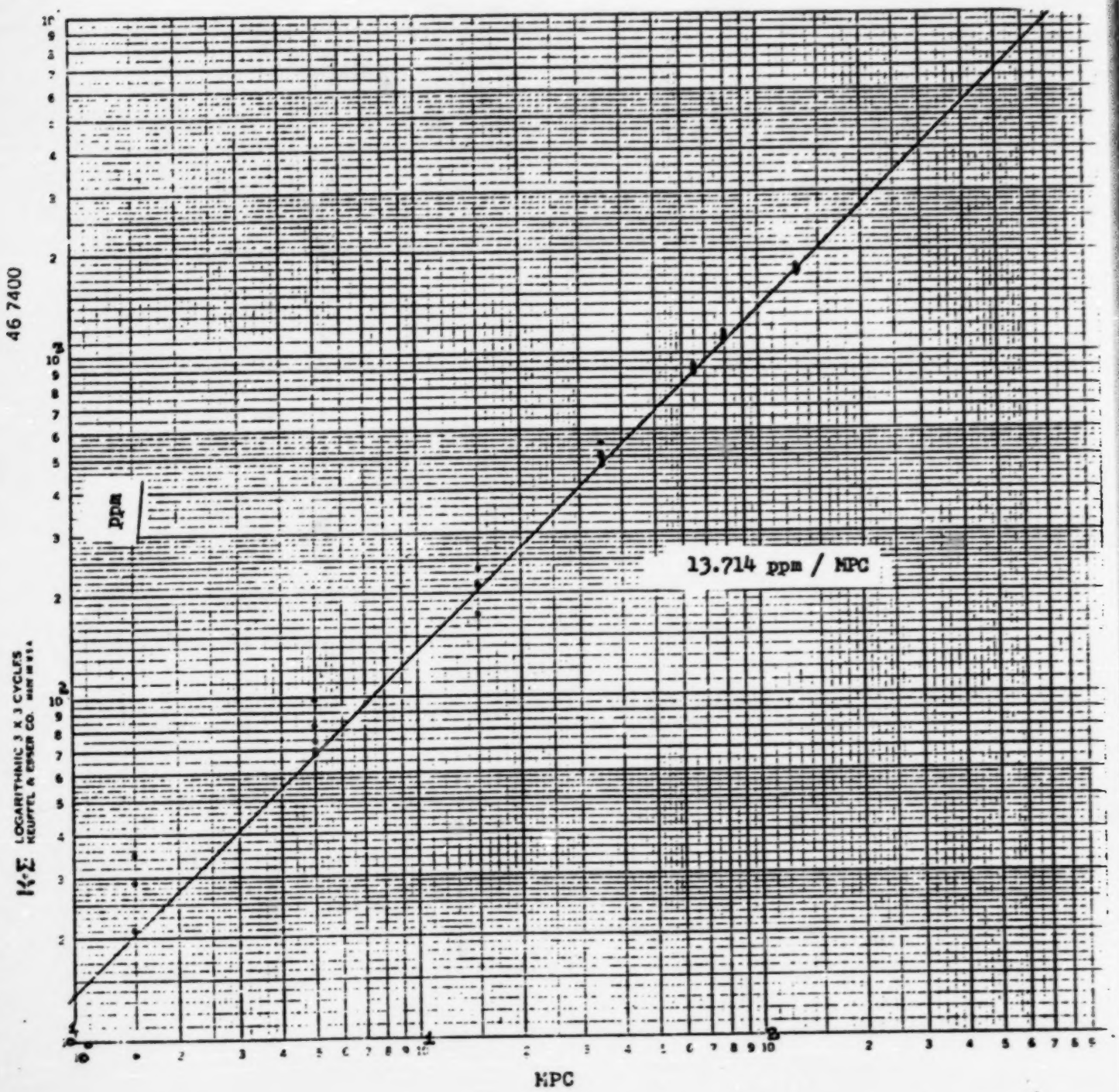


Figure 2.

COUNTER EFFECTIVENESS FOR 15 cc TUBES (ppm/MPC)

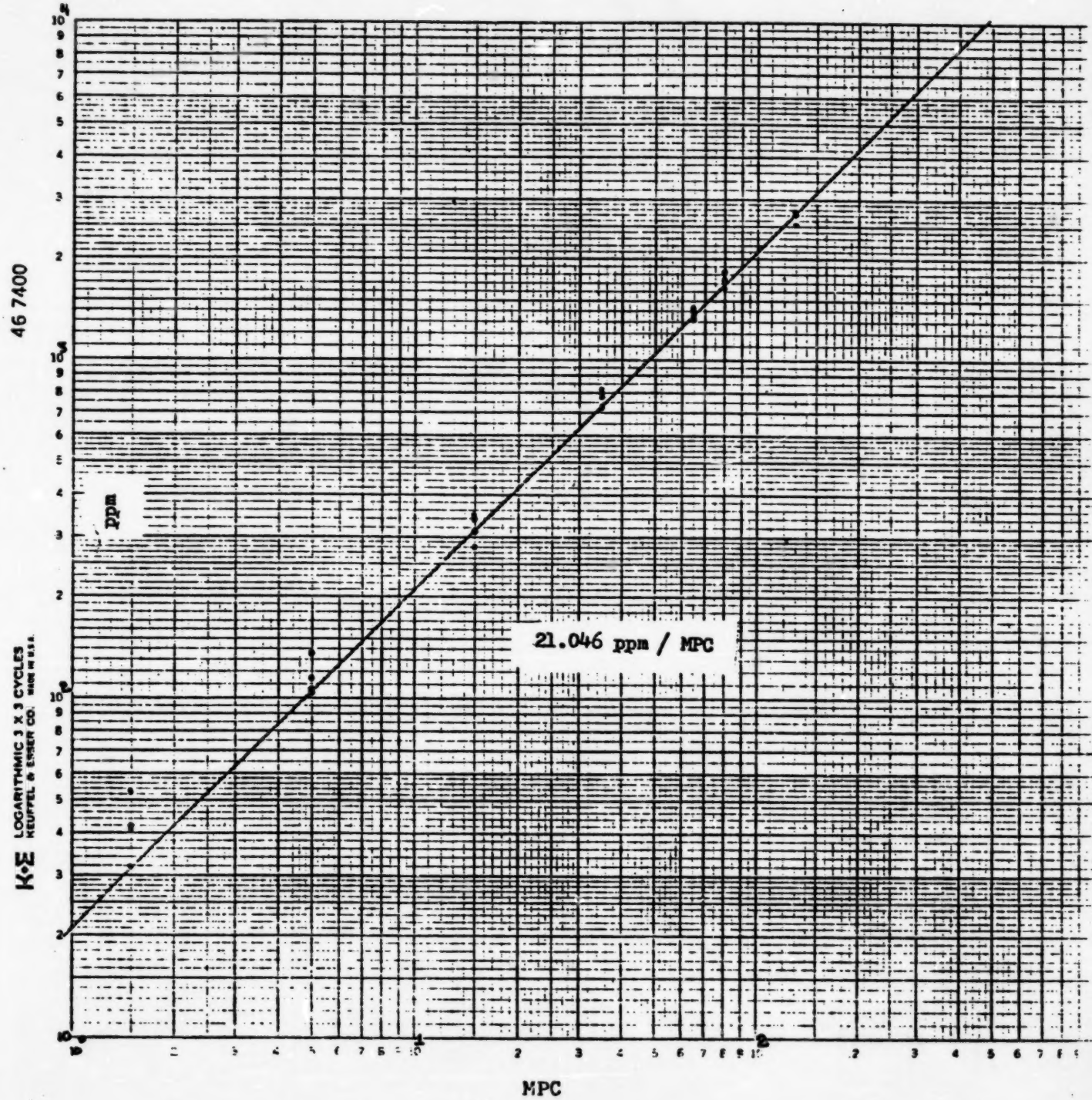
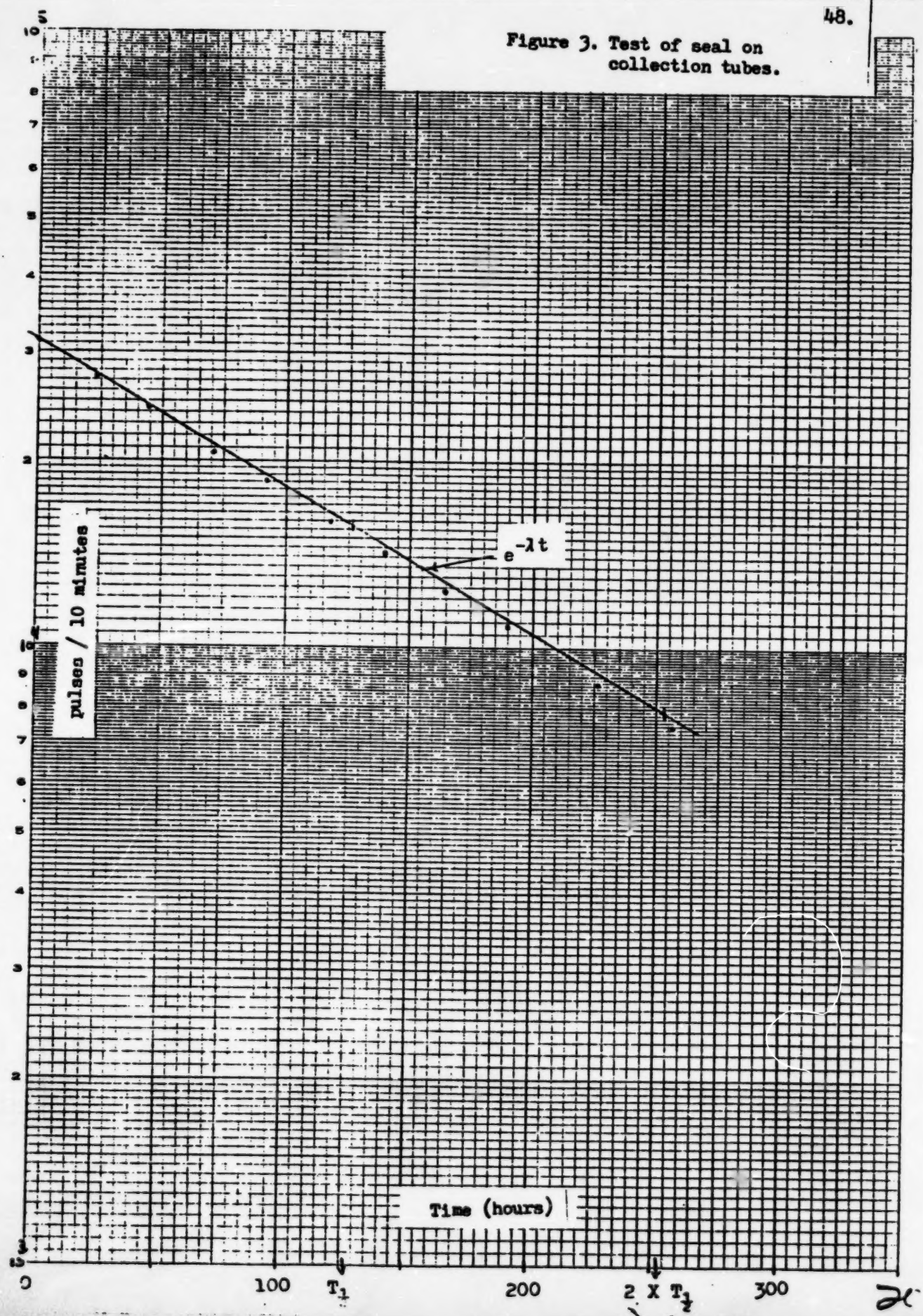


Figure 3. Test of seal on collection tubes.

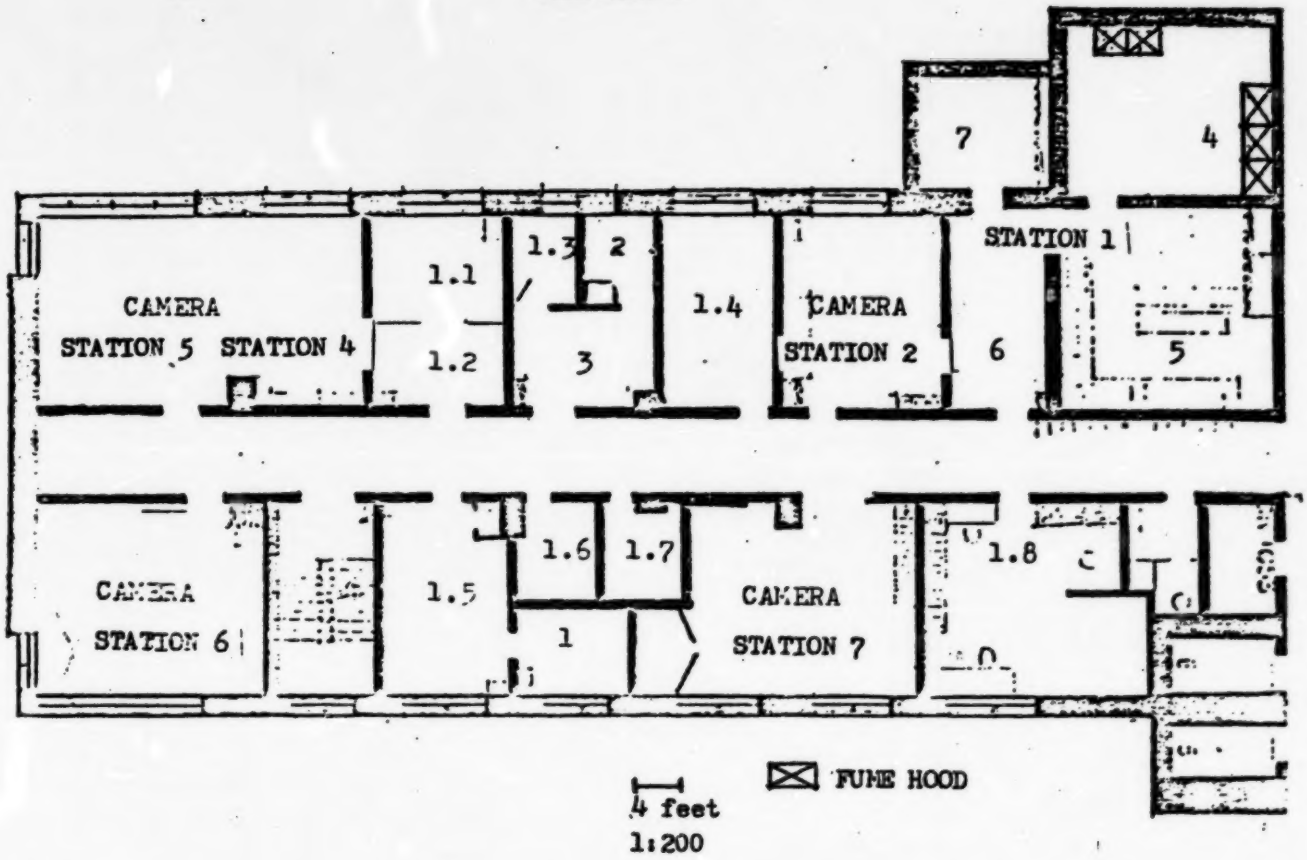


EUGENE DIETZGEN CO.
MADE IN U. S. A.
NO. 340-L210 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
2 CYCLES X 10 DIVISIONS PER INCH

Figure 4.

DEPARTMENT OF NUCLEAR MEDICINE

HOSPITAL A



1.1 Office director
1.2 Office
1.3 Office chief technician
1.4 Office physician
1.5 Office residents
1.6 Office physicist
1.7 Office
1.8 Office reception

2 Darkroom
3 Technicians' lounge
4 Hot laboratory
5 Standard laboratory
6 Injection
7 Gamma counting

Figure 5. Examining room, Hospital A.

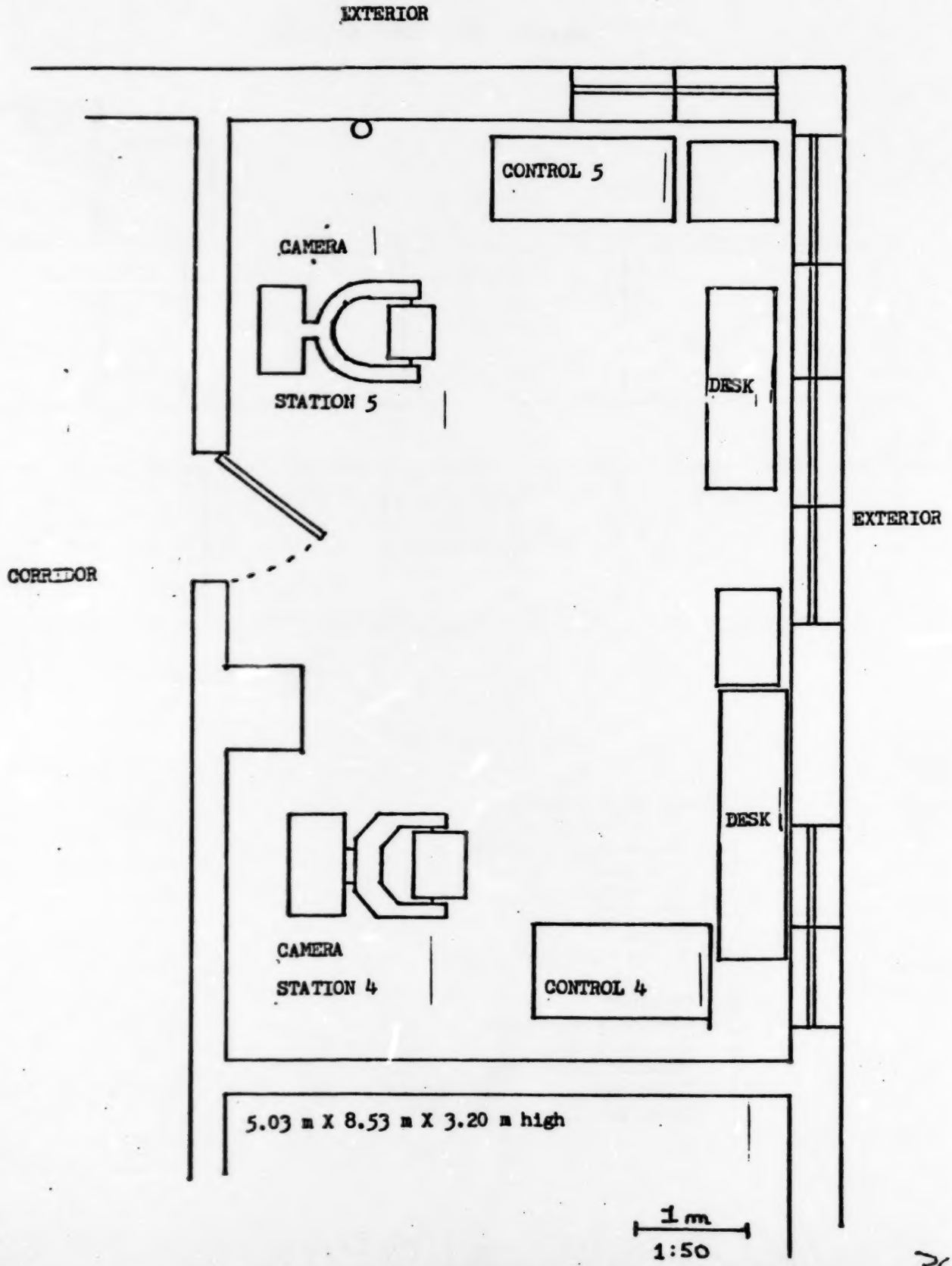


FIGURE 6.

Xe-133 dispenser, Hospital A.

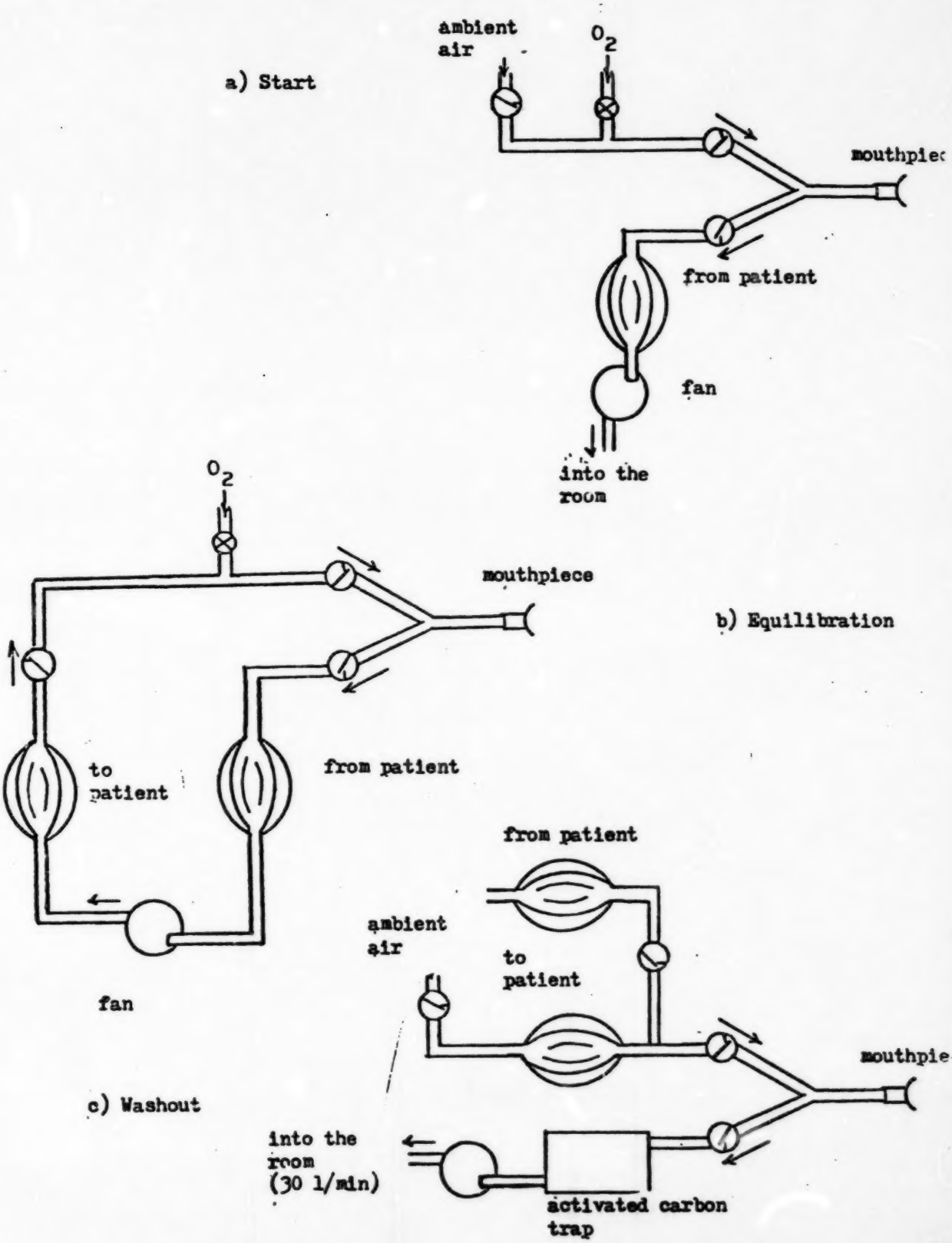


Figure 7. HOSPITAL B.
Department of nuclear medicine.

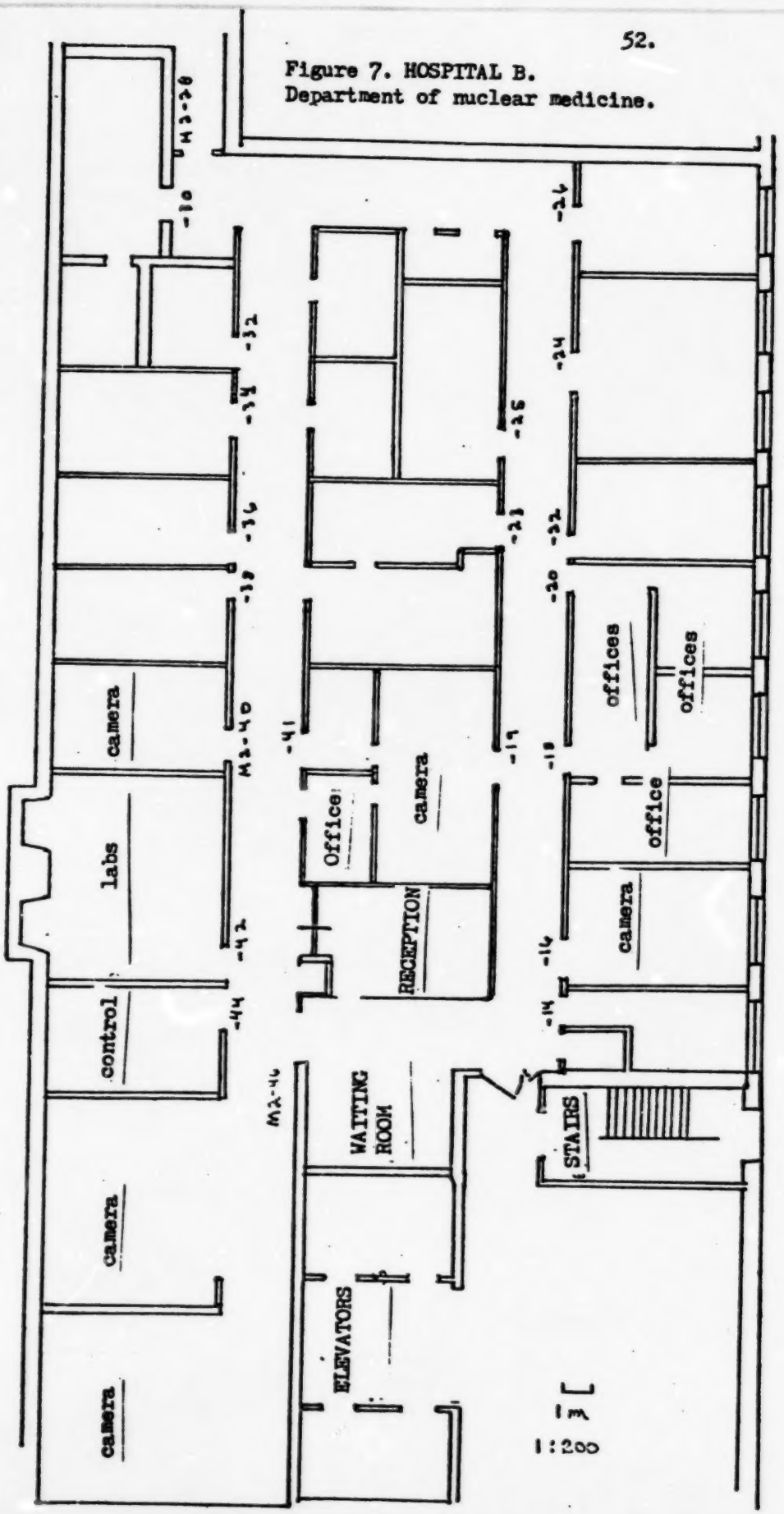


Figure 8. Examining room (#16) Hospital B.

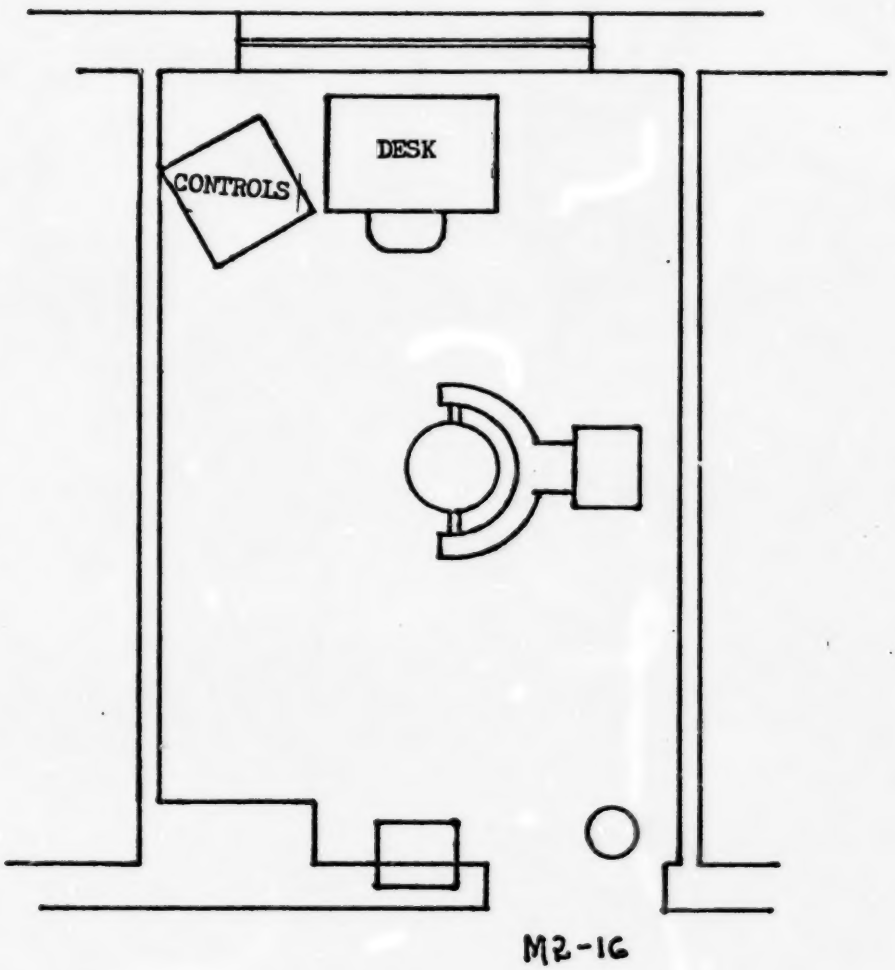


Figure 9. Examining room (#40) Hospital B.

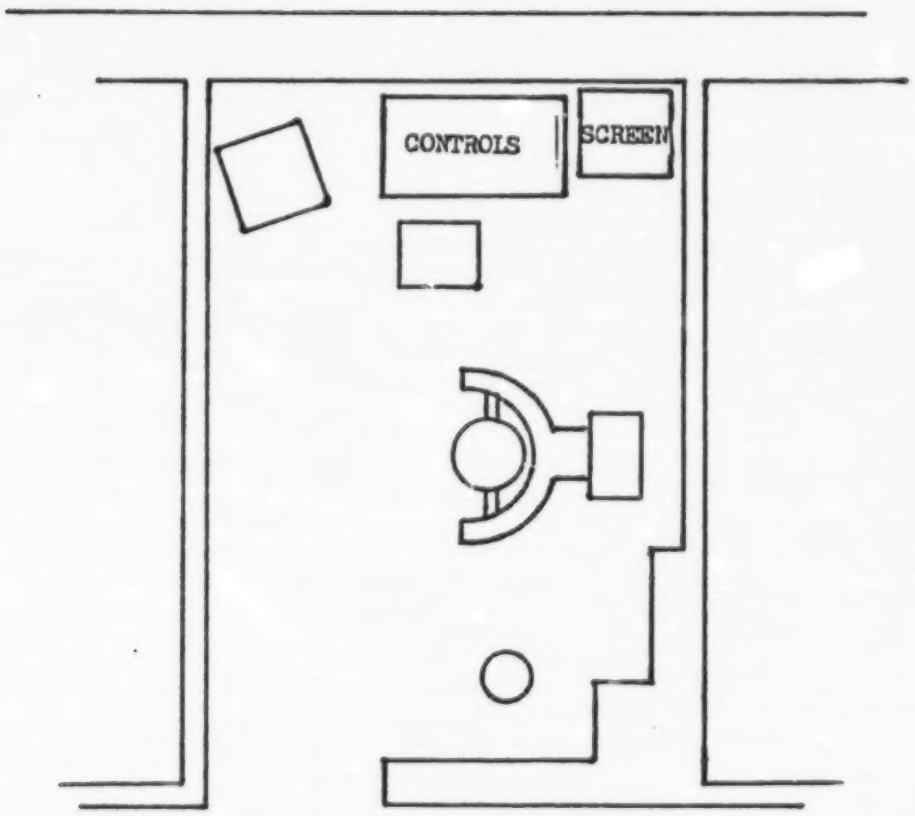
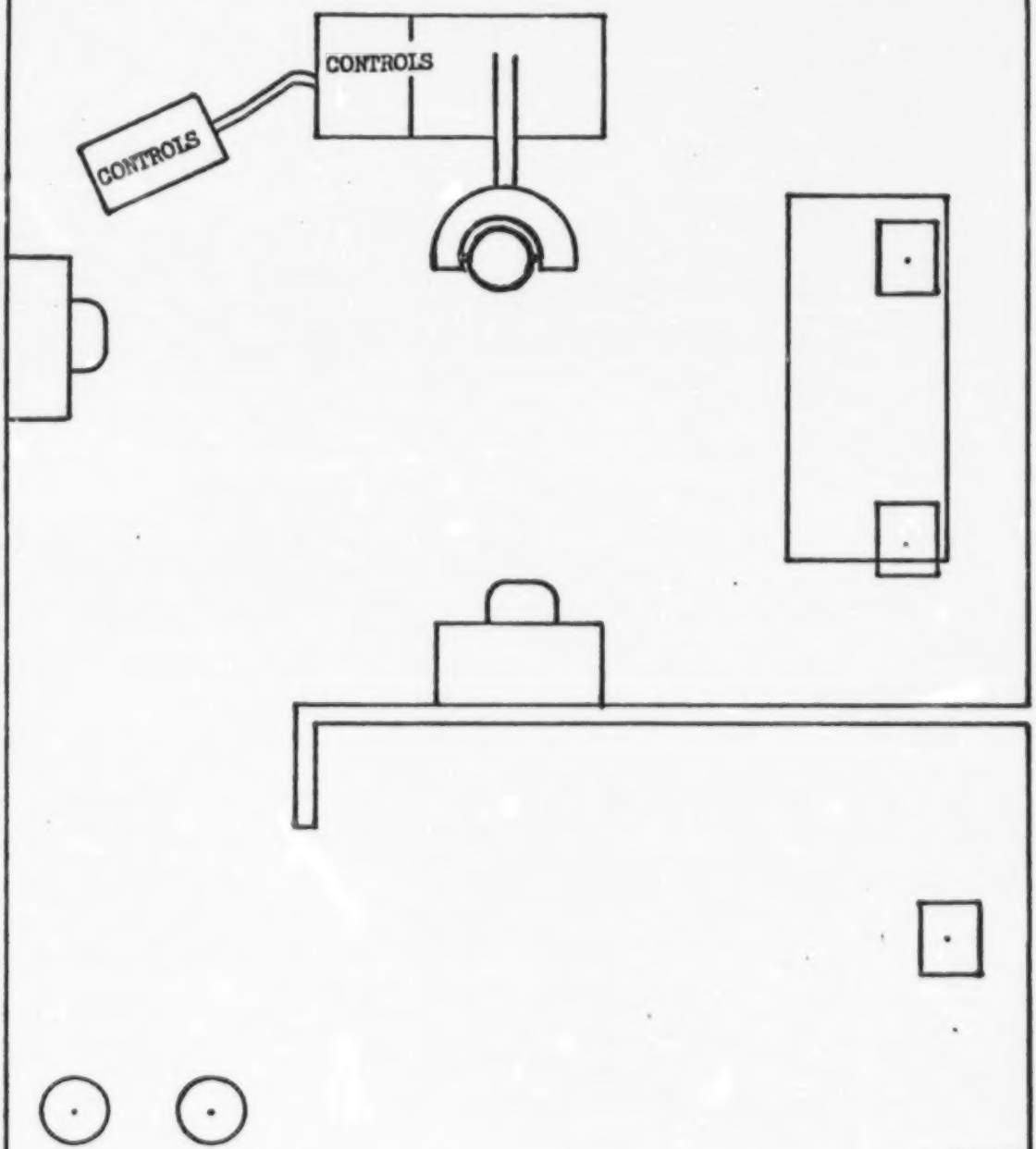


Figure 10. 55.

Examining room (#46) Hospital B.



doors open

1 m

1:50

M2-46

Figure 11.

Xe-133 dispenser, Hospital B.

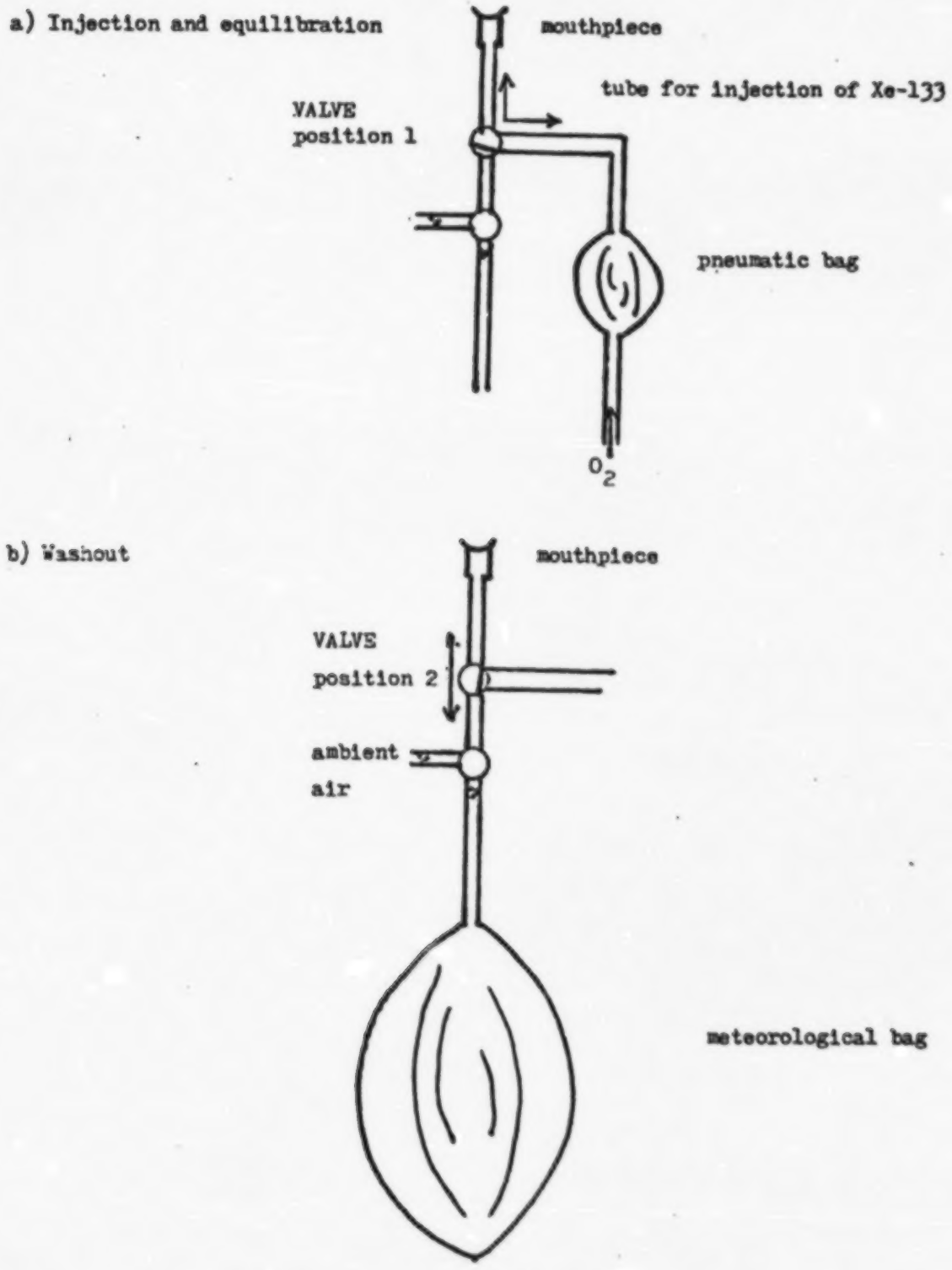


Figure 12.

Hospital A. Sampling sites, STATION 4.

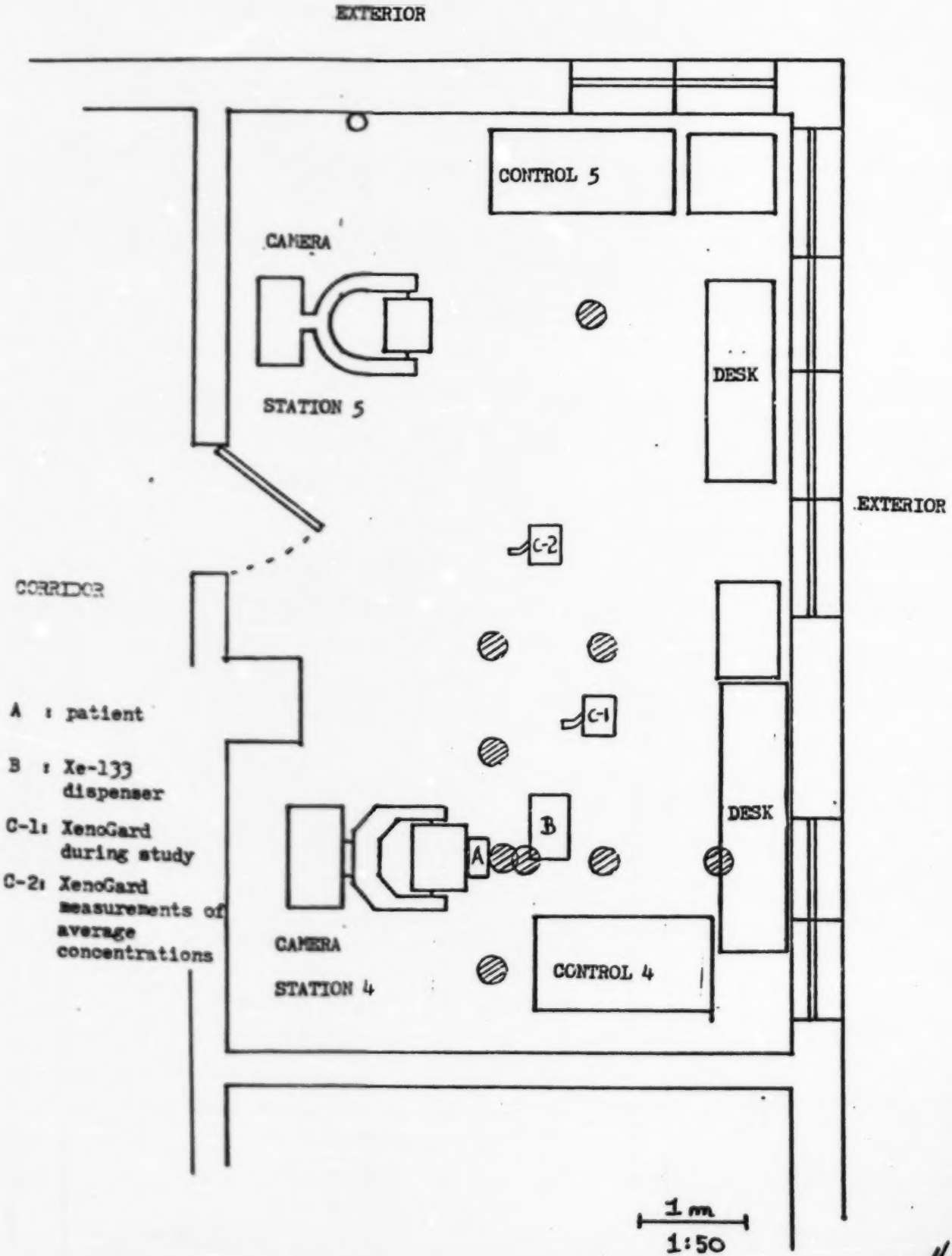


Figure 13.

Hospital A. Sampling sites, STATION 5.

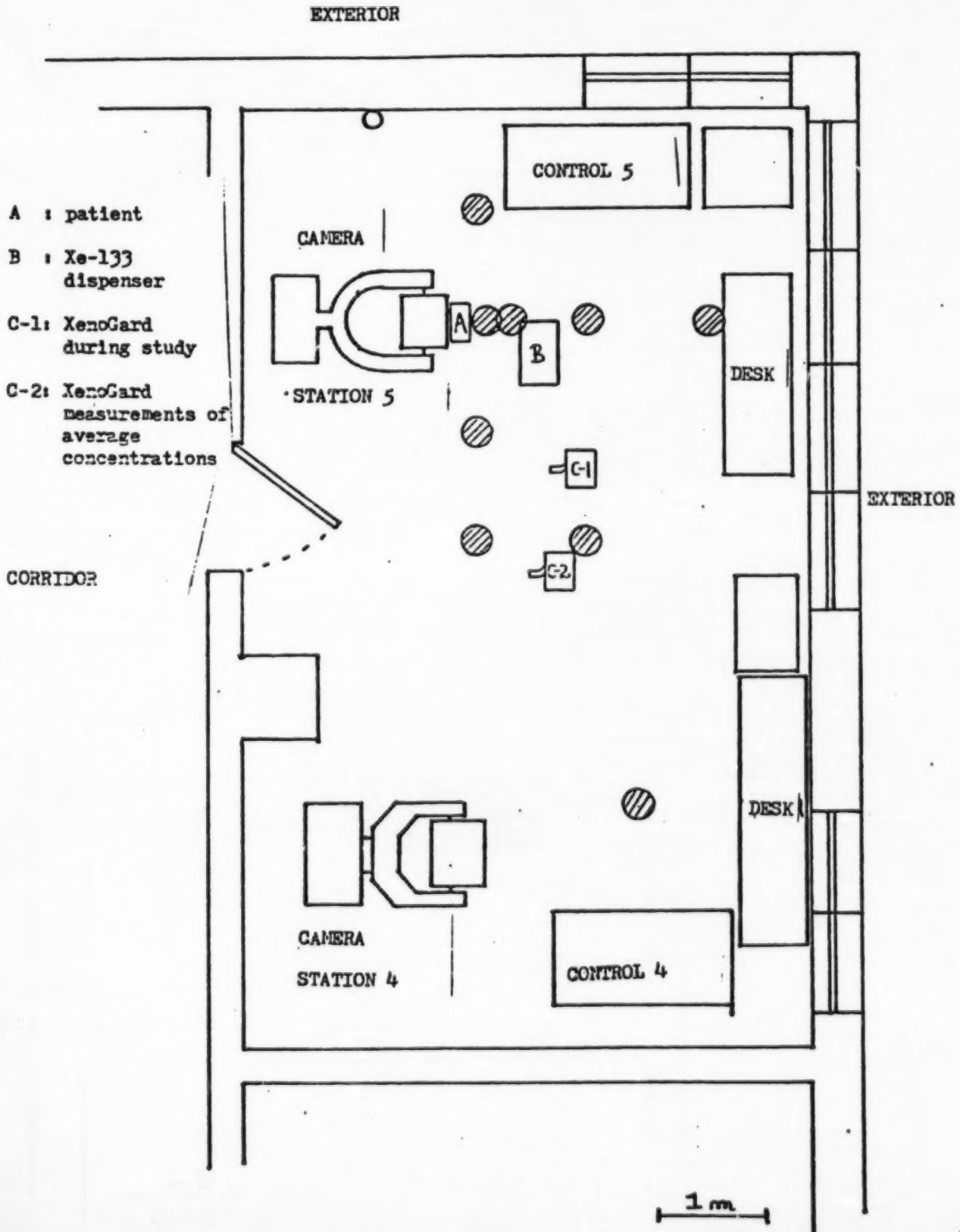
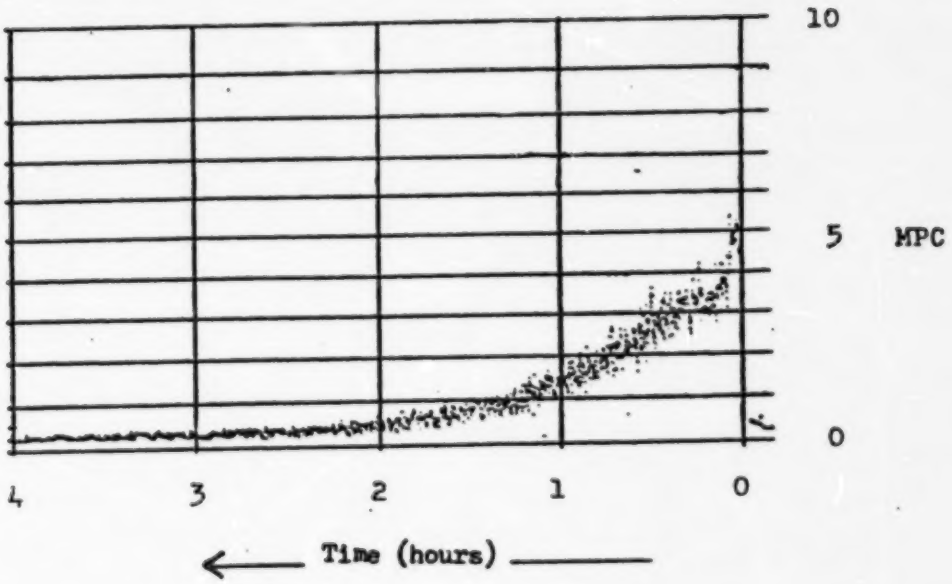


Figure 14.

Variations in air concentrations of Xe-133 over time.
Hospital A, Stations 4 and 5.

a) After one (1) pulmonary ventilation.



b) After three (3) consecutive pulmonary ventilations.

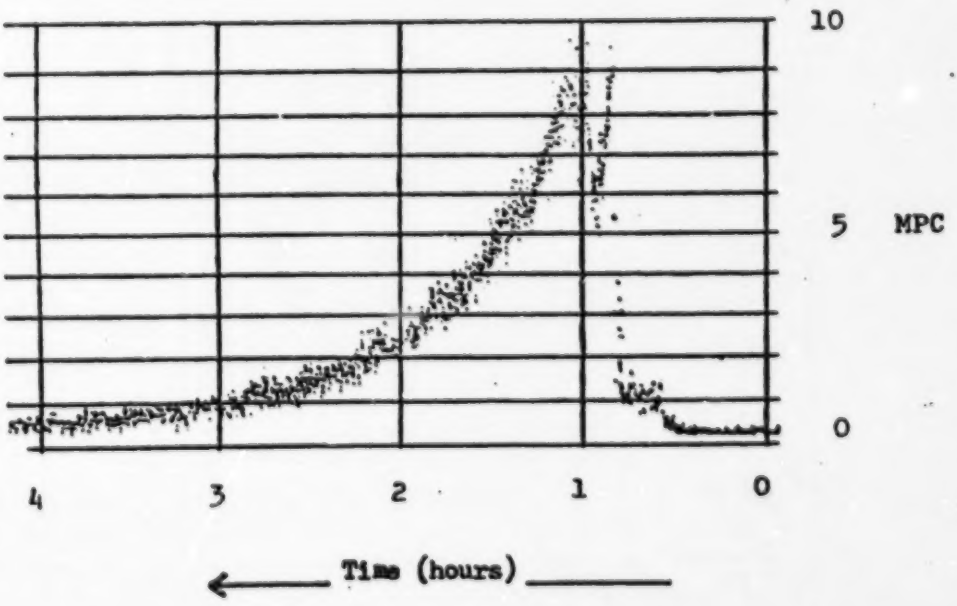


FIGURE 15

Xe-133 concentration over time,

Hospital A, patients 1 and 2.

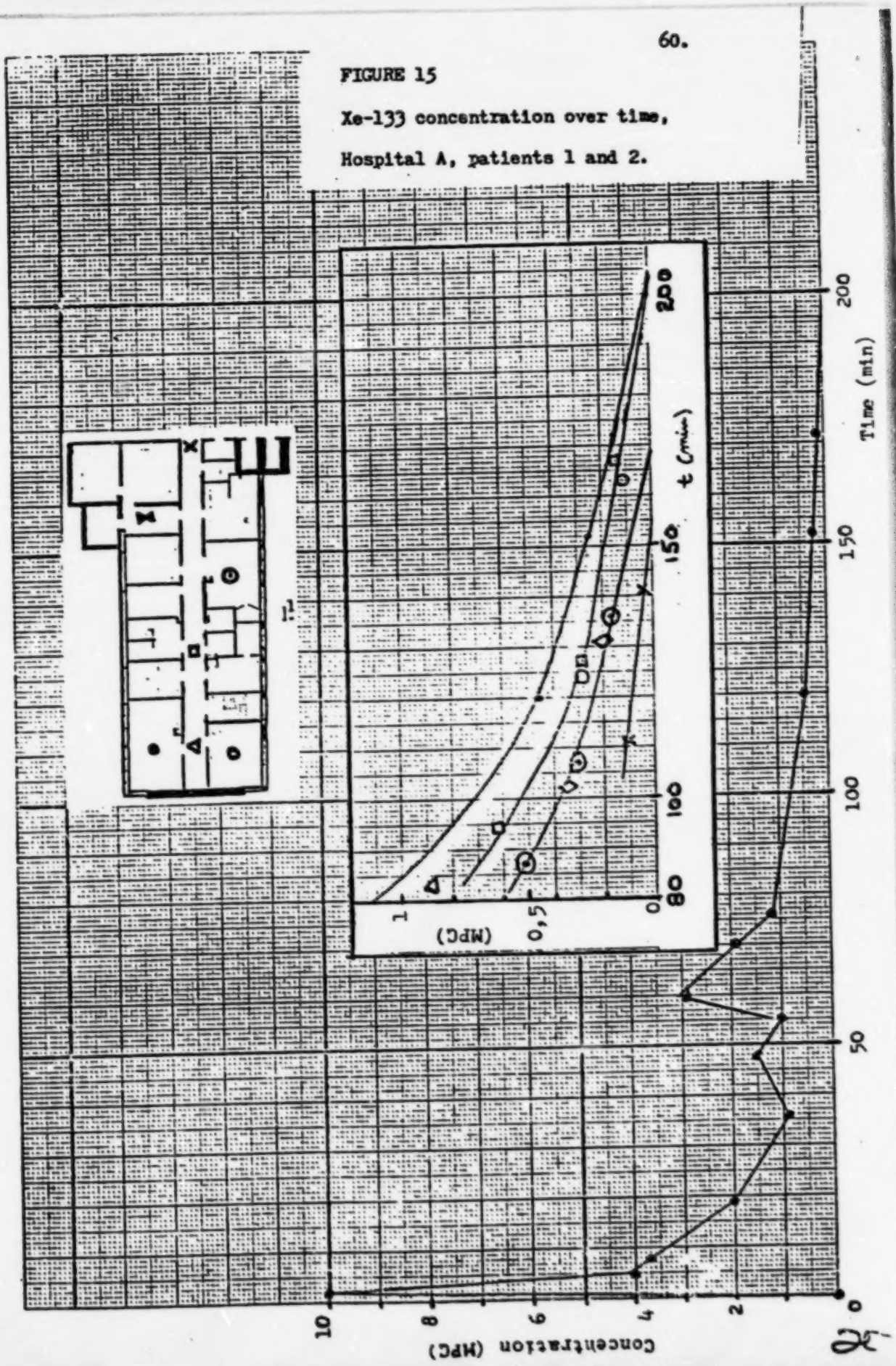


FIGURE 16

Xe-133 concentration over time,

Hospital A, patients 3 and 4.

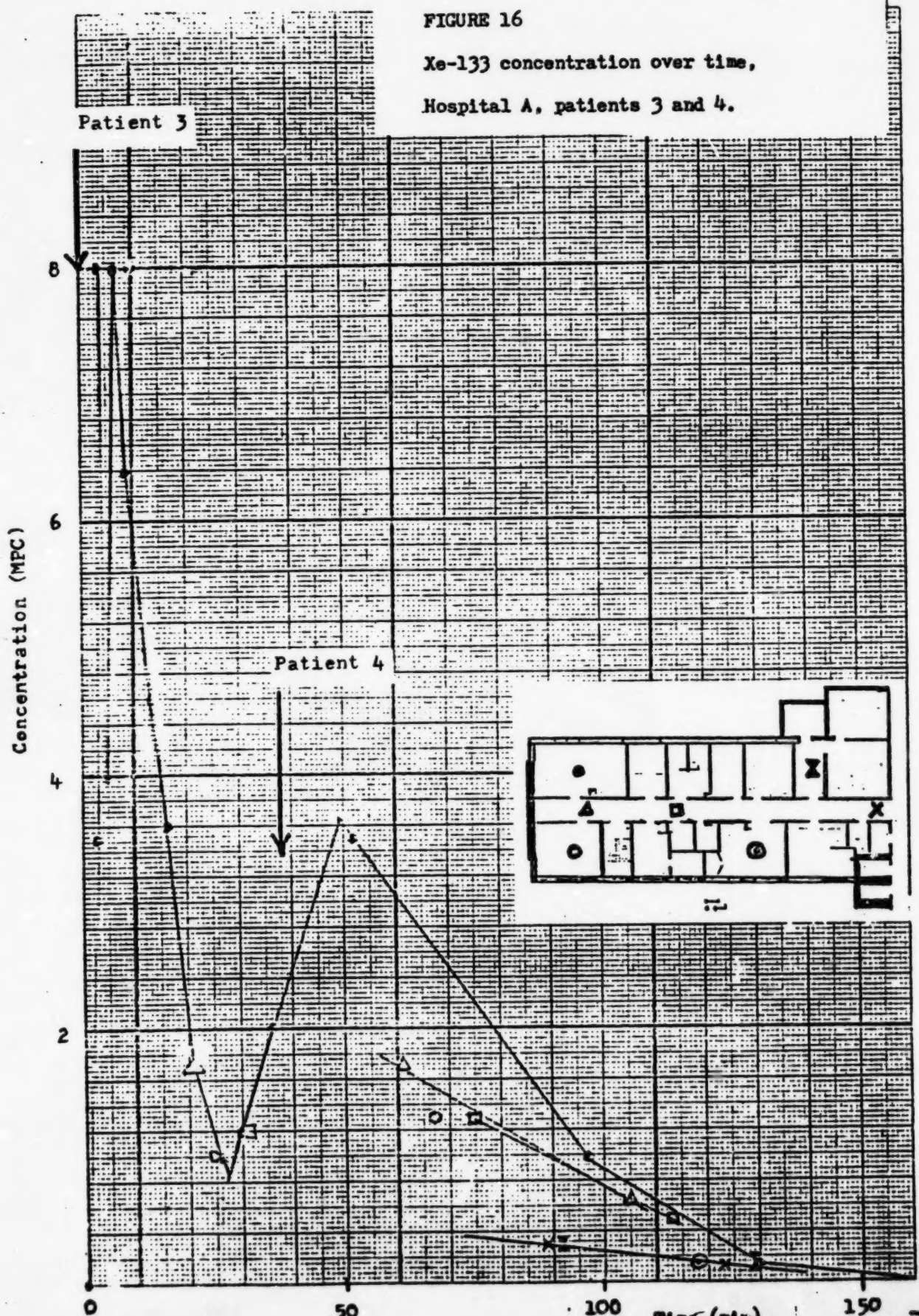


FIGURE 17

Xe-133 concentration over time,

Hospital A, patient 5.

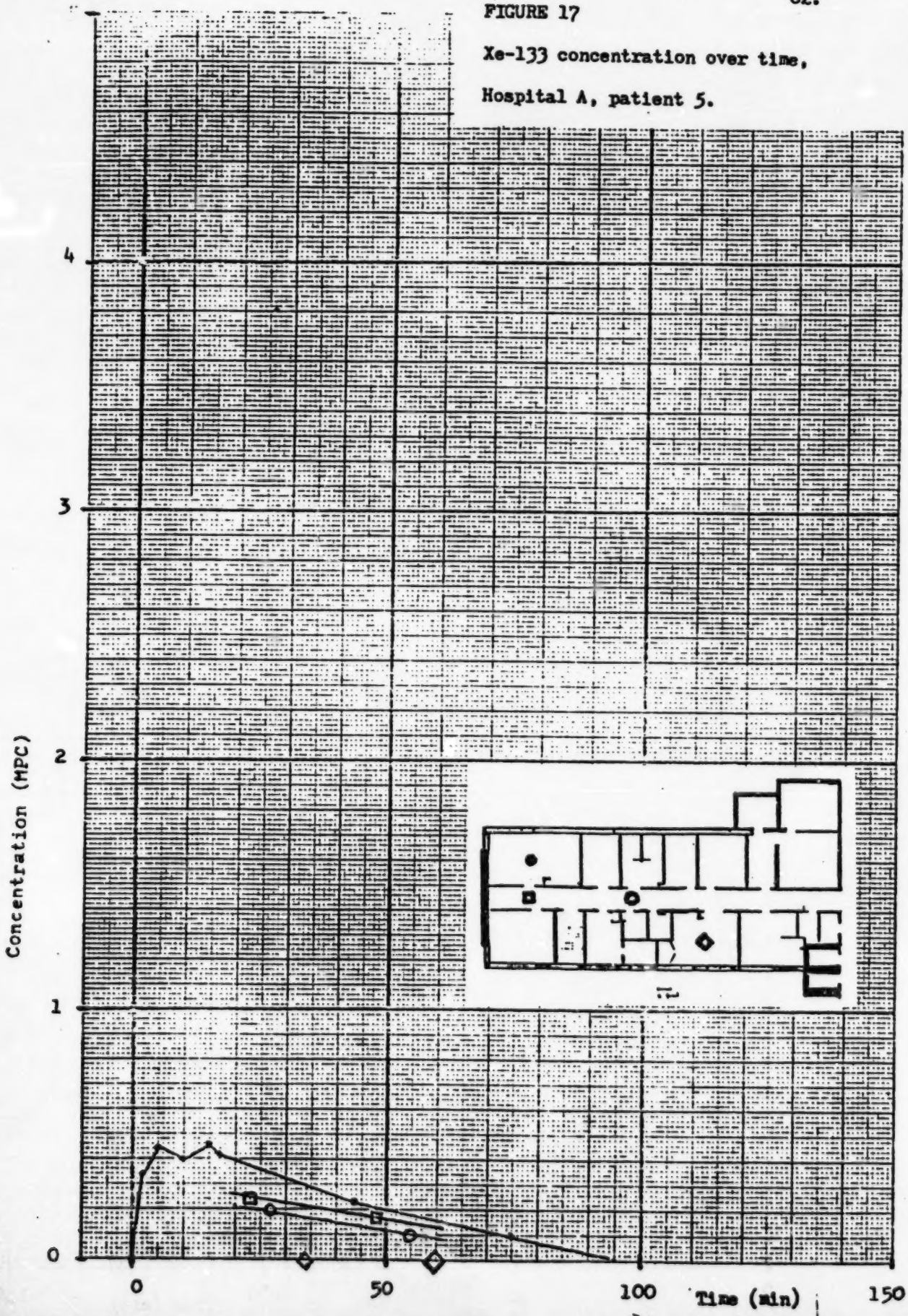


Figure 18.

Hospital B. Sampling sites, Room 16.

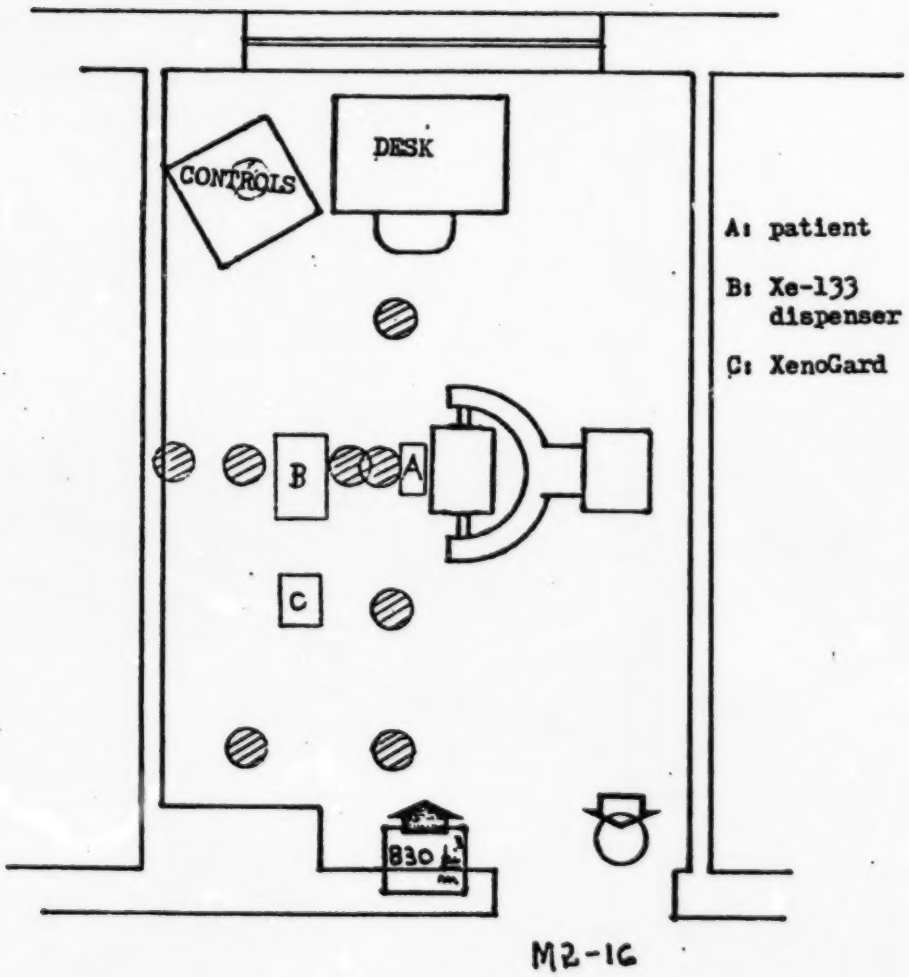
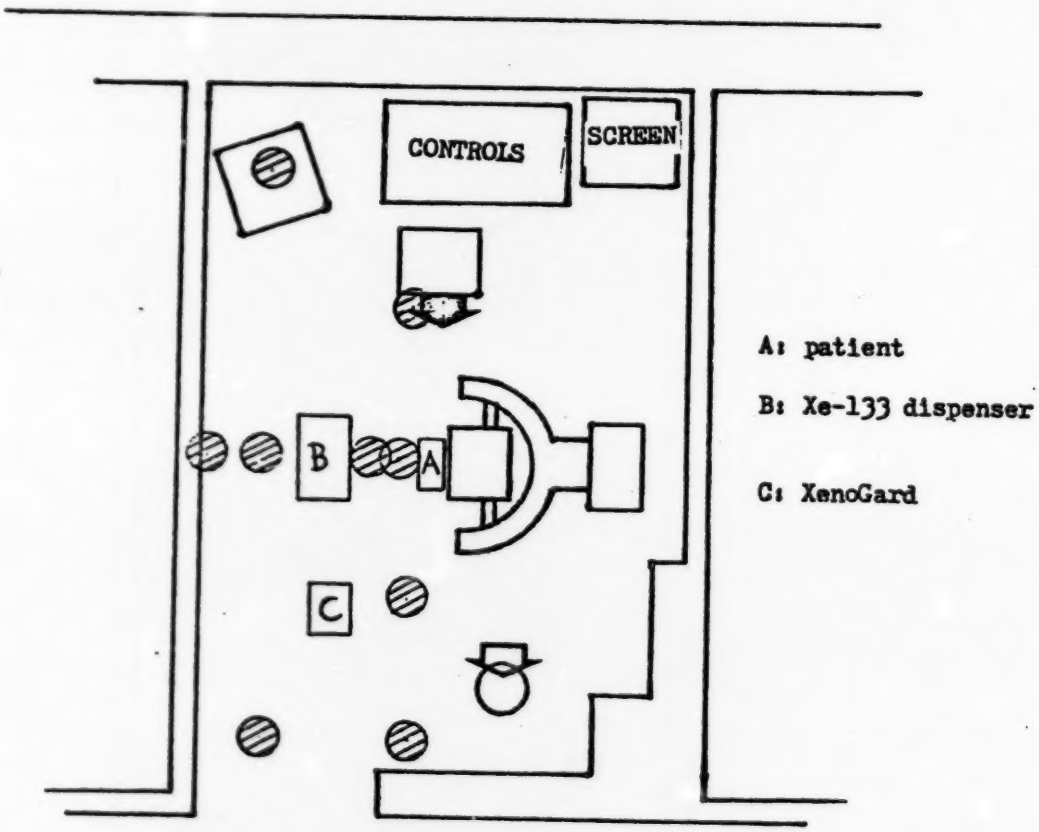


Figure 19.

Hospital B. Sampling sites, Room 40.



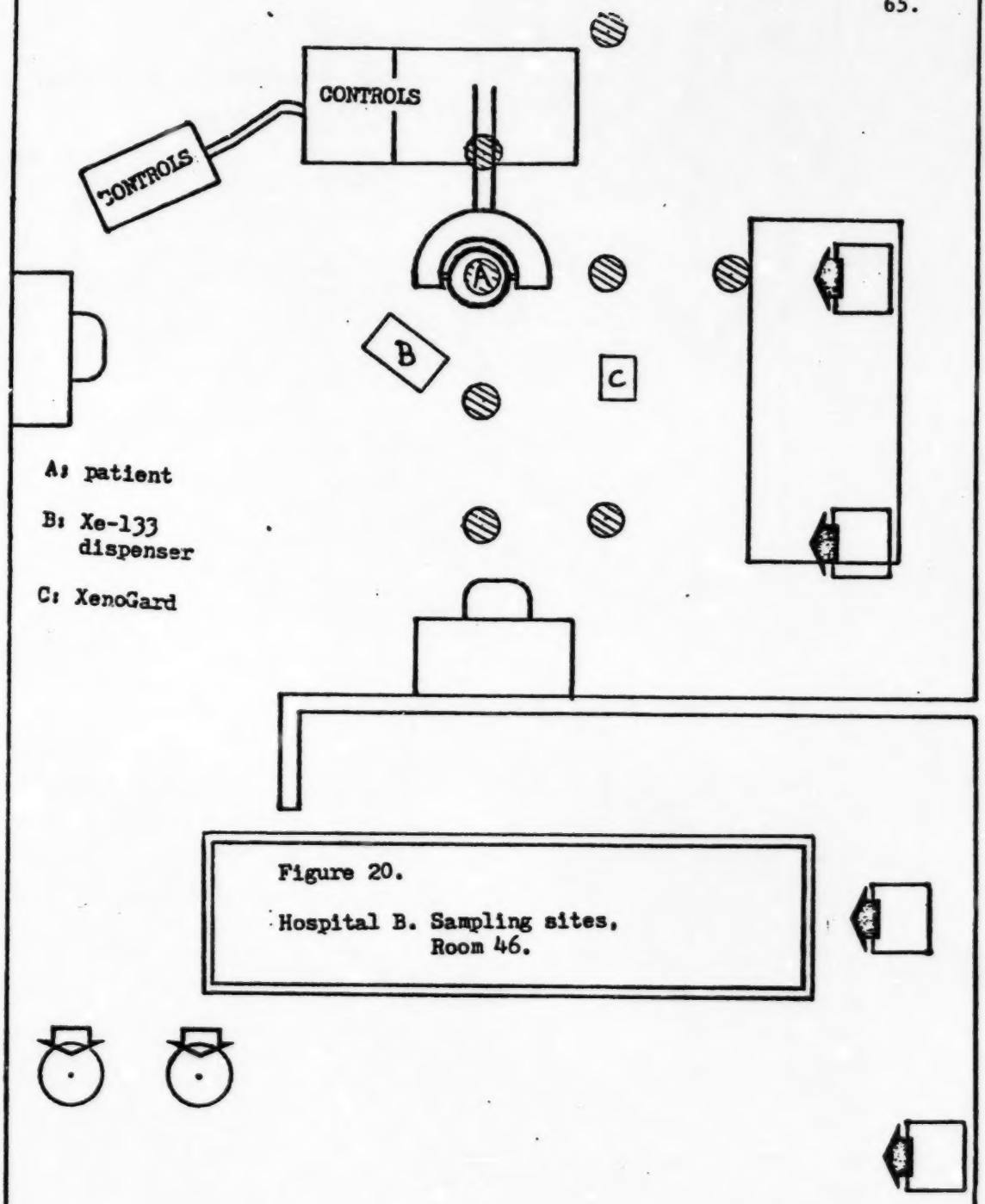


Figure 20.

Hospital B. Sampling sites, Room 46.

FIGURE 21.
Xe-133 concentration over time,
Hospital B, patient 1.

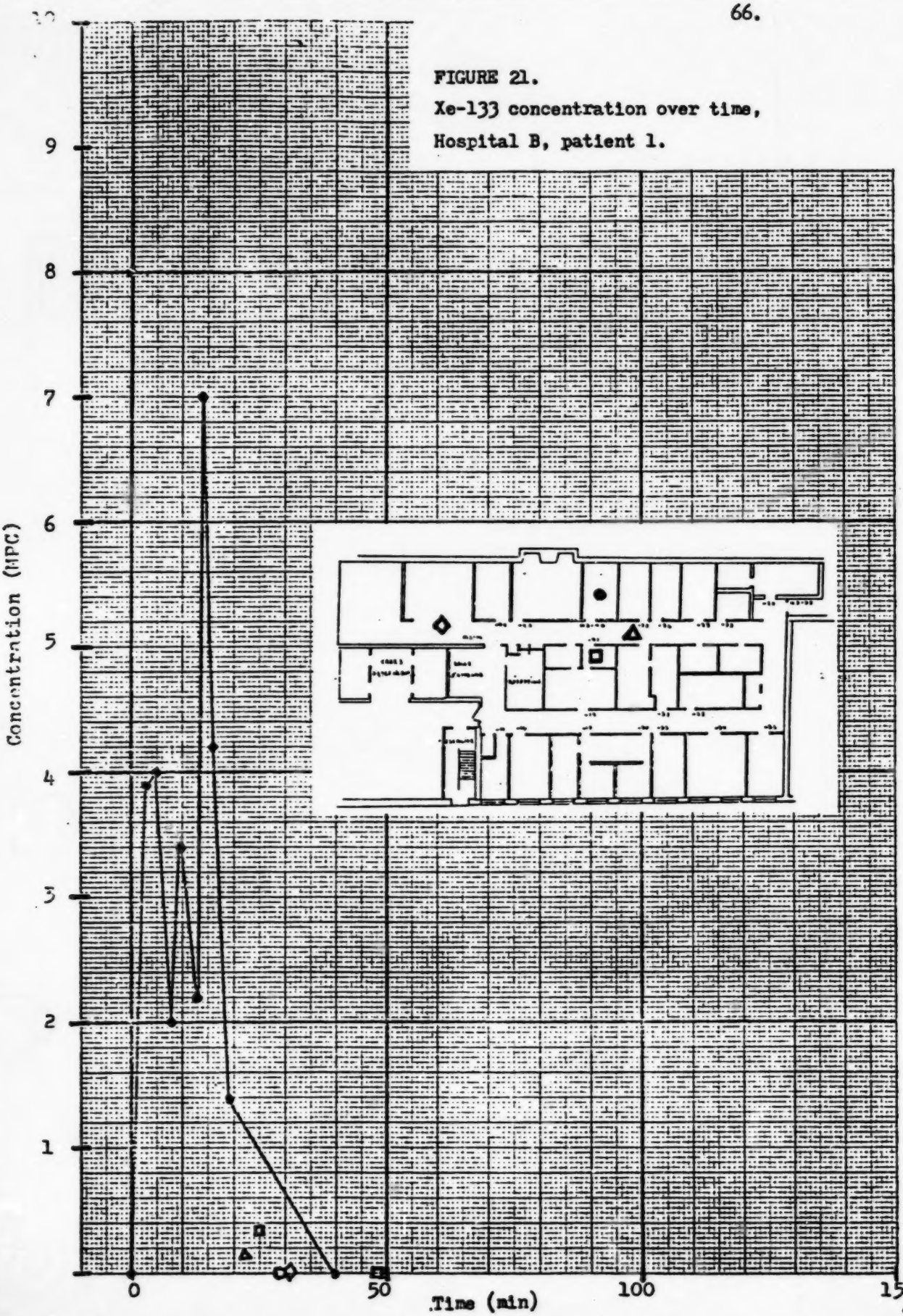


FIGURE 22.
Xe-133 concentration over time,
Hospital B, patients 2 & 3.

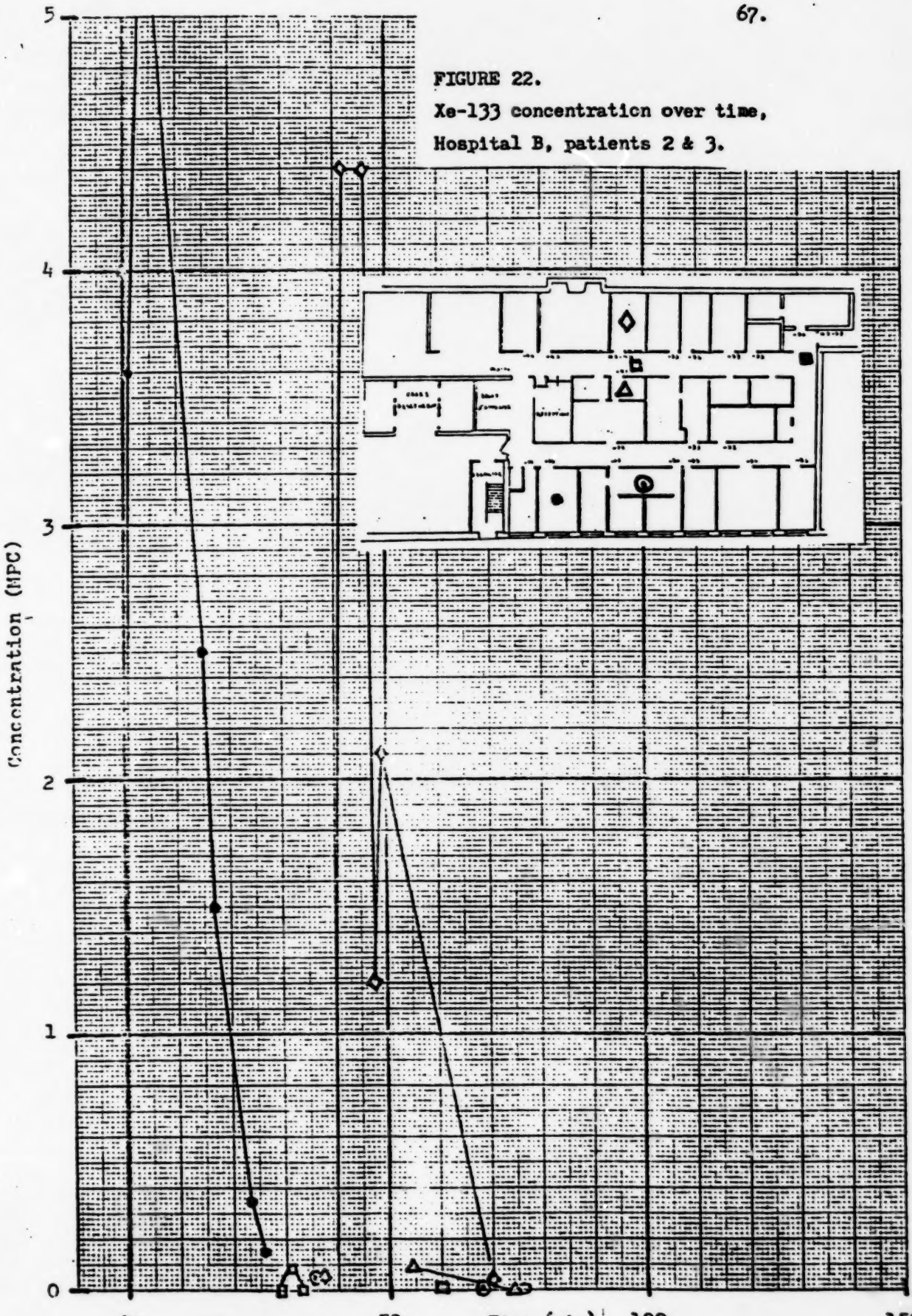
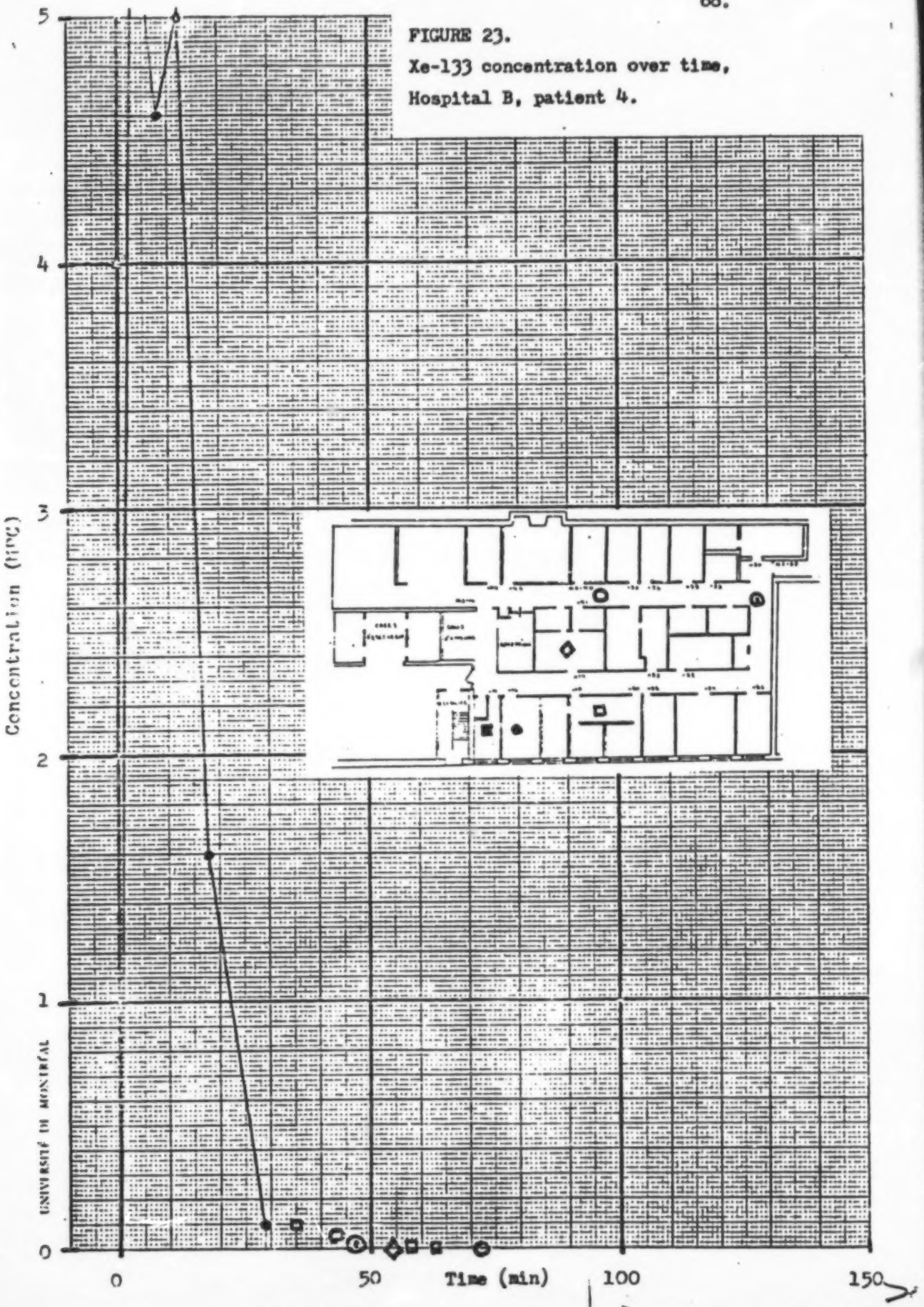


FIGURE 23.
Xe-133 concentration over time,
Hospital B, patient 4.



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